DEVELOPING EVIDENCE-BASED DESIGN METRICS AND METHODS FOR IMPROVING HEALTHCARE SOUNDSCAPES

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DEVELOPING EVIDENCE-BASED DESIGN METRICS AND METHODS FOR IMPROVING HEALTHCARE SOUNDSCAPES

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LIST OF ABBREVIATIONS

Acoustics

BEM: Boundary element method

C50/80: clarity

D50/80: definition

dB: Decibel

dBA: A-weighted sound pressure level

dBC: C-weighted sound pressure level

EDT: Early decay time

FEM: Finite element method

G: Sound strength

IACC: Inter-aural cross correlation

ISM: Image source modeling

JND: Just noticeable difference

LEF/LF/LFC: Lateral fraction

Leq: Equivalent continuous sound pressure level

Lmax: Maximum sound level

Lmin: Minimum sound level

Ln centiles: Exceedance level

Lpeak: Peak sound pressure level

ILD: Inter-aural level difference

ITD: Inter-aural time difference

MLS: Maximum length sequence

NC: Noise criterion

NCB: Balanced noise criterion

PSI: Preferred speech interference

RC: Room criteria

RT: Reverberation time

SI: Speech intelligibility

SIL: Speech interference levels

SNR: Signal to noise ratio

SPL: Sound pressure level

Ts: The centre time

Healthcare and others

AACN: American association of critical care nurses

ASTM: American society for testing of materials

BSI: British standards institute

CEN: European committee for standardization

DDHNS: Disturbance due to hospital noise survey

ICU: Intensive care unit

ISO: International standard organization

OSHA: Occupational safety and health administration

RGD: Relative grid distance

SCCM: Society of critical care medicine

SD: Standard deviation

WHO: World health organization

VF: Visual fragmentation

SUMMARY

Healing and clinical work requires a complex choreography of architectural acoustic design in healthcare settings that is only beginning to be understood. In most healthcare settings, medical staff members conduct vital tasks that may have life-and-death implications. Patients visit hospitals to heal. Their expectations include fast recovery, restful sleep, and privacy (e.g., speech privacy). However, sound environment qualities of care settings often fall far from supporting the mission of hospitals. There is strong and growing evidence showing that soundscapes in healthcare settings impact healing, errors and stress for patients, families and staff but it is still not clear what measures of the sound environment best predict key healthcare outcomes and what design strategies best impact those measures. By using a multi-method approach, this study aims to develop a toolkit of evidence-based design strategies by statistically defining the relationships between three types of variables: (1) architectural floor-plate design metrics, (2) acoustic metrics, and (3) occupant response.

In Chapter 2, the study explores the effects of hospital sound environments on caregiver health and performance outcomes by comparing the sound environments of a traditional critical care setting (ICU) with an award winning design ICU. For the objective and subjective assessment of sound environments of the two ICUs, continuous noise level (field) measurements and an online survey of caregivers are utilized. According to statistical analysis results, critical care sound environments with different designs can vary drastically and impact caregivers` perceived wellbeing and overall task

performance. Differences between healthcare sound environments and nurses` annoyance and loudness perceptions can also vary during different times of the day and days of the week. Moreover, particular noise sources such as impulsive noises are likely to dominate the ICU sound environments and interfere with perceived caregiver health and performance. Despite their extensive use, traditional noise metrics sometimes may not be effective in capturing unique the characteristics of healthcare sound environments. This study validates the effectiveness of a new more detailed noise metric, “occurrence rate”, in capturing the differences between acoustic characteristics of healthcare sound environments.

In Chapter 3, the study analyzes the association between healthcare sound environments and specific type caregiver tasks: “critical sound tasks” (i.e., patient auditory monitoring). In order to gain detailed information about critical sound tasks conducted by caregivers and assess caregiver`s ability to conduct these tasks in different care settings, an online survey is utilized. Interesting differences are found between critical sound task performances of caregivers working in two wards with different designs. In Chapter 3, the review of literature clarifies specific acoustic characteristics of sound environments necessary for auditory monitoring. In particular, reverberant qualities of sound environments can have significant negative impacts on sound localization performance of the human auditory system. Analysis of the survey data also provides important baseline information (e.g., types of critical sounds and listening locations) for the following phases of the research. For example, caregivers reported that they frequently monitor sounds in the corridors of their units as well as other locations such as patient rooms and nurse stations. However, the association between architectural floor-plate design and acoustics of inter-connected hospital corridors has not been investigated in previous research. To support the development of sound task supportive healthcare environments, in the following phases of this research more controlled studies are conducted via acoustic simulation analysis. In Chapter 4, an overview of room-acoustics parameters, the sound behavior in proportional and non-proportional spaces and the association between floor-plate design and acoustics are provided by reviewing literature. In Chapter 5, the effectiveness of the acoustic simulation tool in estimating the reverberant characteristics of inter-connected corridors is validated by comparing the predicted and measured acoustic outcomes. In Chapter 6, the statistical analysis results clarifies the association between floor-plate design characteristics (e.g., corridor length, number of turns and branch number) and reverberant qualities of inter-connected nursing unit corridors. Various theoretical models are generated based on the heuristic design analysis of various nursing units. Acoustic qualities of these theoretical models are analyzed by the validated acoustic simulation program. Finally in Chapter 7, acoustic modeling predictions of the real-world wards and field measurements are utilized in Chapter 6 to verify the proposed effects of floor-plate design on reverberant qualities of corridors.

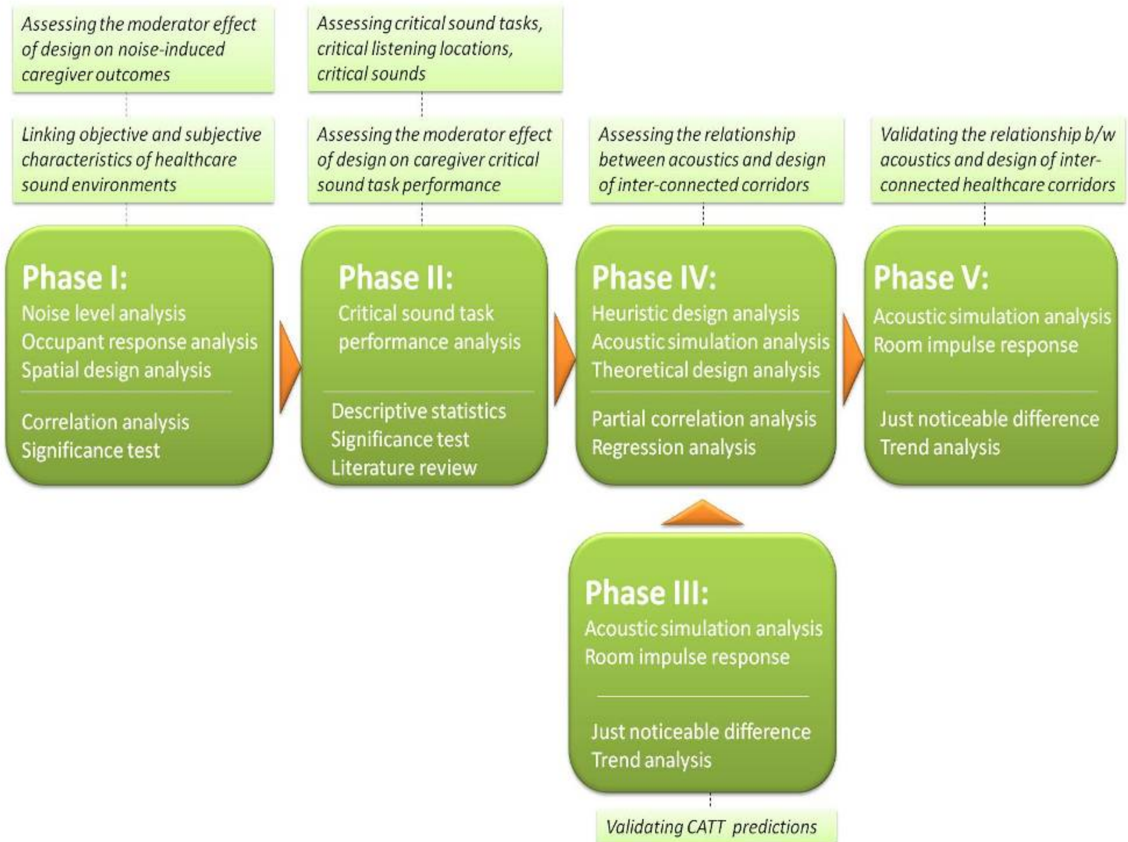


Figure 1.1 Phases of the research *(See Appendix A for the definition of terms and descriptions of different analysis methods included in the graph above)*

CHAPTER 1

RESEARCH PROBLEM

1.1 BACKGROUND

Hospitals are getting noisier each year (Busch-Vishniac et al., 2005). There is strong and growing evidence of the negative impacts of a poor hospital soundscape such as staff stress, loss of productivity, medical errors, and oral miscommunication (Busch-Vishniac et al., 2005; Flynn et al., 1999; Morrison et al., 2003; Ryherd, Persson Waye, & Ljungkvist, 2008; Topf, 1988; Topf, & Dillon, 1988). Patients may suffer from sleep disturbance, anxiety, cardiovascular arousal, and decreased wound healing (Baker et al., 1993; Freedman et al., 2001; Gabor et al., 2003; Hagerman et al. 2005; Hsu, Ryherd & Persson Waye, 2009; McCarthy, Quimet, & Daun, 1992; Parthasarathy, & Tobin, 2004; Wysocki, 1996). In critical care units, poor soundscapes might even have life-and-death implications as caregivers rely on auditory cues such as help calls, and alarms. To date, a poor hospital soundscape has primarily been addressed using engineering-oriented solutions such as sound-absorbing acoustic materials. However, the engineering methods remain limited because of the complex nature of hospital soundscapes and the limited availability of acoustic materials meeting stringent hygienic hospital requirements (Busch-Vishniac et al., 2005; Ryherd, Persson Waye, & Ljungkvist, 2008). Additionally, while many hospitals are clearly noisy there is limited documentation of their actual characteristics, particularly their architectural layouts. This is surprising as it is well known that there are significant impacts of architectural design features on the soundscapes of music halls, offices, and other spaces (Long, 2006). The few studies that do exist show conflicting results; for example, studies conducted before and after acoustic renovations in different healthcare settings report inconsistent improvements in the soundscape (Blomkvist et al., 1996). This limits the ability of architects to effectively design healing soundscapes.

1.2 PROBLEM STATEMENT

A healing healthcare environment is quiet, orderly, and conducive to patient recovery and safety, family comfort, and employee health and productivity. Too often, healthcare facilities are noisy and stressful; the complex auditory environment, or "soundscape," has long been a key source of complaints. While there is an urgent need for effective soundscapes in healthcare settings, there are surprisingly no rigorous efforts to enhance the architects` contribution in addressing this problem from the early design phase through building commissioning. This study conducts quasi-experimental and experimental research to relate specific architectural layout metrics, acoustic metrics, and hospital occupant outcomes.

1.3 SCOPE AND OBJECTIVES

Primary objectives include:

- Objective and subjective noise level analyses;
    - Develop new acoustic metrics and methods effective in capturing unique characteristics of healthcare sound environments

    - Test the effectiveness of traditional and more detailed acoustic metrics in capturing the differences between sound environments of different healthcare settings
    - Assess whether traditional and more detailed acoustic metrics relate to perceived qualities of sound environments and nurse outcomes
    - Assess the effects of particular noise sources on perceived caregiver outcomes
- Soliciting feedback from caregivers via online surveys
    - Assess the importance of specific caregiver tasks (visual vs. auditory patient monitoring) for patient safety
    - Identify critical listening locations
    - Identify critical sounds for patient safety
    - Identify which acoustic qualities of sound environments negatively affect critical sound tasks of caregivers
    - Assess auditory monitoring performances of caregivers in different care settings with different designs
- Just noticeable difference analysis
    - Validate CATT acoustic modeling program predictions
- Heuristics design analysis
    - Identify floor-plate design characteristics of nursing unit corridors
    - Provide basis for theoretical design analysis
- Pilot study: Acoustic analysis (via impulse response) of interconnected corridors in the educational buildings

    - Provide basis for the theoretical design analysis
    - Assess the link between acoustics and design of inter-connected corridors based on field measurements
- Experimental study: Theoretical design analysis (via simulation)
    - Statistically link acoustics and floor-plate shape qualities of nursing unit corridors based on acoustic modeling predictions
    - Statistically link acoustics and floor-plate design qualities of particular hallways based on acoustic modeling predictions
- Validation study: Acoustic analysis (via simulation and impulse response) of real world hospital wards
    - Validate the proposed relationship between design and acoustics of inter-connected corridors

1.4 RESEARCH QUESTIONS

Chapter 2

Chapter 2 introduces the findings of three empirical studies. The main goal of these studies is to analyze the impact of sound environments on staff outcomes. Empirical study 1 assesses the objective and subjective noise levels at different locations in the two ICUs. Empirical study 2 documents the objective and subjective noise levels during different times at each unit nurse stations by conducting the occurrence rate analysis and assessing nurse perceptions. Empirical study 3 compares the level of nurse disturbance due one of the dominant impulsive sounds, clinical alarms, in the two ICUs. Specific research questions addressed in Chapter 2 are:

1. Do acoustic qualities (objective and subjective) of healthcare sound environments with different architectural designs differ from each other?
2. Do objective qualities of healthcare sound environments statistically relate to subjective qualities of healthcare sound environments?
3. Which noise measures are effective in capturing the differences between critical care sound environments?
4. Do different types of noise sources impact caregiver outcomes similarly in different healthcare settings?

Chapter3

Chapter 3 provides a comprehensive overview of factors related to auditory monitoring and introduces the finding of a case study comparing nurses` auditory monitoring performance in two ICUs with different architectural designs. Specific research questions addressed in Chapter 3 are:

1. Which acoustic qualities of sound environments relate to auditory monitoring of critical sounds?
2. Is auditory patient monitoring as critically important as visual patient monitoring?
3. What are the critical sounds that caregivers monitor for patient safety?
4. Where do caregivers frequently monitor critical sounds in their units?

5. Do patient auditory monitoring performances of caregivers differ in healthcare settings with different architectural designs and acoustic qualities?

Chapter 4

Chapter 4 provides an overview of room-acoustics parameters, the sound behavior in proportional and non-proportional spaces, and the association between floor-plate design and acoustics by reviewing literature. Specific research questions addressed in Chapter 4 are:

1. Do the characteristics of sound behavior in proportional spaces differ from the characteristics of sound behavior in the non-proportional spaces?
2. What are the design factors that affect the behavior of sound in proportional and non-proportional spaces?

Chapter 5

Chapter 5 introduces the findings of various impulse response measurements and acoustic simulation analysis conducted to assess the validity of acoustic modeling tools in estimating the acoustic qualities of non-proportional spaces. The specific research question addressed in Chapter 5 is:

1. Are the differences between predicted (via CATT acoustic modeling program) and measured (via impulse response measurements) acoustic outcomes perceptible?

Chapter6

Chapter 6 presents the results of a heuristic design analysis and statistically explores the association between acoustics and design variables of interconnected corridors via three empirical studies. First, a pilot study is conducted in the inter-connected corridors of educational settings. To test the findings of the pilot study, a more controlled follow up study (Empirical Study 1) is conducted by using CATT acoustic simulation program. Another theoretical design analysis (Empirical Study 2) is also conducted to assess the effects of overall floor-plate shape characteristics of inter-connected corridor systems on averaged reverberation time values. Specific research questions addressed in Chapter 6 are:

1. What are the floor-plate design characteristics of nursing unit corridors?
2. Do overall floor-plate shape qualities of inter-connected corridors relate to their acoustic qualities?
3. Do floor-plate design qualities of particular hallways in an interconnected corridor setting relate to their acoustic qualities?

Chapter 7

Chapter 7 assesses the validity of the previous study findings (in Chapter 6) by analyzing the acoustics of real-world hospital ward corridors via impulse response measurements and acoustic simulation analysis. Specific research questions addressed in Chapter 7 are:

1. Do field measurements and acoustic modeling predictions of the real-world wards verify the findings of Chapter 6?
    a. Do reverberant qualities of hallways with different corridor length differ from each other?
    b. Do reverberant qualities of hallways with different number of branches differ from each other?
    c. Do reverberant qualities of hallways with different number of turns (from the sound source) differ from each other?
    d. Do reverberant qualities of inter-connected corridors with different floor-plate shape qualities differ from each other?

Chapter 8

Chapter 8 summarizes the findings of each chapter and defines the study contributions, limitations and future work.

1.5 SIGNIFICANCE

This study addresses the issue of wellbeing and task supportive healthcare soundscapes by diagnosing problematic aspects of healthcare sound environments and proposing design strategies. The outcomes of this study:

- Address increasing urgency for the development of effective soundscapes in healthcare settings. The study assesses the effectiveness of intended design strategies in improving healthcare soundscapes. The U.S. is starting one of the largest healthcare construction programs in its history, expected to exceed $76 billion a year by 2011(FMI, 2006; Zimring, & Bosh, 2008). Potentially, the results will have resonating effects on the health of society, as 4.9 million Americans work in hospitals and many more are treated in them (U.S. Dept of Labor, 2008).

- Verify the necessity of using effective acoustic metrics and methods for the diagnosis of problematic aspects of healthcare soundscapes.
- Provide new acoustic metrics to capture the unique characteristics of healthcare sound environments and validate their effectiveness in predicting occupant outcomes.
- Diagnose highly problematic sound sources and highlight the necessity of collaboration between medical equipment engineers/designers and healthcare providers.
- Provide detailed information about the characteristics of healthcare soundscapes to support informed decision making and collaboration between architects, engineers and healthcare providers.
- Expand principles of statistical acoustics that have been widely used to explore the relationship between acoustics and design of more well-understood spaces to the complex hospital settings.
- Establish the relationship between hospital floor-plate design and acoustic metrics.
- Allow architects to design hospital layouts that are more conductive to occupant health and productivity. To date, a hospital soundscape has primarily been

addressed using engineering-oriented solutions such as sound-absorbing materials.

CHAPTER 2

HOSPITAL SOUNDSCAPES AND STAFF OUTCOMES

Chapter 2 introduces objective and subjective qualities of hospital sound environments by reviewing literature and conducting three empirical studies.

2.1 LITERATURE REVIEW

2.1.1 Noise levels in hospitals

Growing research on hospital acoustics indicate that hospitals have noisy and multi-source sound environments. Background noise levels in hospitals have been consistently increasing (Bush-Vishniac et al. 2005). The study conducted a timeline analysis of noise levels reported in thirty-five studies published over the last forty-five years. It was found that since 1960, day time and night time hospital noise levels have risen from 57dBA to 72dBA and from 42 to 60dBA respectively. According to World Health Organization (WHO) guidelines, background noise levels particularly in the patient rooms should not exceed 30dBA for day time and 35dBA for night time (Berglund et al., 1999).

2.1.2 Hospital Noise Metrics

Previous research has used different metrics to measure and describe the sound environment. Most research to-date has focused on characterizing *overall noise levels.* Equivalent (Leq), minimum (Lmin), maximum (Lmax), and peak (Lpeak) sound pressure levels have been most commonly reported. This may be based on the practicality and convenience of these measures, and because they are incorporated into various guidelines such as WHO. Leq, Lmin, Lmax and Lpeak sound levels provide a good general overview of the sound environment, but are limited in usefulness. More *detailed acoustic measures* such as the exceedance level (Ln), reverberation time (RT), speech intelligibility (SI), and frequency analysis or noise criteria indicators of spectral content have been less commonly reported. In the ICU, there are a diversity of noise sources such as alarms, ventilation systems, conversation, and medical equipment that contribute to a complex, varying sound environment. More detailed acoustic measures are important to more fully understand the spectral character of the sound environment, its behavior over time and the potential to interfere with speech.

2.1.3 Hospital noise level measurement methods

There is a good deal of variance in the methods applied during the sound sample collections in the previous literature on ICUs. Compared to other spaces, noise levels in the ICU patient rooms have been commonly documented. Measurements typically took place either in a representative patient room (Christensen, 2005; McLaughlin et al., 1996; Ryherd, Persson Waye, & Ljungvist, 2008) or in more than one patient room with different features such as distance to the nurse station, occupied-unoccupied, number of patient beds (Aaron et al., 1996; Aitken, 1982; Blomkvist et al., 2005; Bush-Vishniac et al., 2005; Hilton, 1985; MacKenzie, & Galbrun, 2007; Meyer et al., 1994; Morrison et al., 2003; Moore et al., 1998; Williams, Drongelen, & Lasky, 2007). There is general consistency in the location of the sound meter, with most studies locating the microphone as close as possible to patient head to capture what the patient hears while avoiding any interference with nurse work flow. Hanging the microphone from the top of the medical tower in the patient room has been introduced as a practical solution (Ryherd, Waye, & Ljungvist, 2008).

Different durations have been used in the data collection, ranging from a few minutes to 168h, with 24h recordings most widely used. A few ICU noise studies have also conducted measurements at the nurse stations using 24h or 168h durations (Blomkvist et al., 2005; Bush-Vishniac et al., 2005; Moore et al., 1998). Busch-Vishniac et al. (2005) also described the sound environment of hallways. There are also differences in the sound level meter response times used, with many using a slow response time (1s) as suggested by the Occupational Safety and Health Administration (OSHA) for typical occupational noise measurements (ANSI 1996; Bush-Vishniac et al. 2005; Williams, Drongelen, & Lasky, 2007). Some studies used fast response time (0.125s) as suggested by WHO to better capture fluctuations (MacKenzie, & Galbrun, 2007; Ryherd, Waye, & Ljungvist, 2008). Averaging intervals also ranged from 5s to 24h (e.g., 30s, 1min, 5min). Among ICU-noise studies the use of 1min averaging interval was most common. Measurements were often analyzed as a function of time, with day time and night time average sound levels commonly reported. Weekdays were most commonly measured, with limited data on weekends. Morrison et al. (2003) and Ryherd, Waye, & Ljungvist (2008) considered day and night time based on twelve hour nurse shifts (day time:7am-7pm; night time: 7pm-7am). MacKenzie, and Galbrun (2007) considered the day and night time periods based on WHO guidelines (16h day time:7am-11pm; 8h night time:11pm-7am).

2.1.4 Hospital noise and its effects on staff members

The acoustic environment in hospitals can affect all occupants, including staff, patients, and visitors. Related with the focus of this study, the following discussion is mostly limited to its effects on staff members: stress and annoyance; work performance; health outcomes and work overload. Further information about how hospital acoustics may impact patients and visitors can be found in sources such as Busch-Vishniac et al. (2005) and Ryherd et al. (2008). The staff's wellbeing, efficiency and effectiveness in delivering care and performing critical tasks is critical to maximize patient safety, satisfaction, and care quality in ICUs.

Stress and Annoyance

ICUs are stressful care settings and the stress can be exacerbated by the sensory overload caused by environmental factors, including the high noise levels. Stress is the individual's appraisal of a mismatch between perceived demand and perceived self-capabilities to cope (Clarke, 1984). Depending on the severity and duration, stress may lead to illness (e.g., elevated blood pressure, indigestion) and behavioral changes (e.g., sadness, depression, negative attitudes). Anxiety is a psychological response to environmental stimuli or activity producing arousal (Gast, & Baker, 1989). Excessive anxiety can be detrimental and lead to different health effects such as sleep deprivation and confusion. Like anxiety, annoyance is one of the early psychological responses which reflect the negative quality of the environment stimuli (Baker, 1984), and it relates to the intrusion of a stimulus on a mental or physical activity.

In one study, higher average sound pressure levels predicted higher nurse heart rate, perceived stress, and perceived annoyance levels in a Pediatric-ICU (Morrison et al., 2003). The sound pressure level was measured using the A-weighted equivalent sound pressure level (LAeq). In this study, the sound levels were averaged every 30min. Regression analysis was used to correlate the LAeq with continuously recorded heart rate and saliva samples and stress/annoyance ratings that were also collected in every 30min. During 3h periods, samples were collected from 11 nurses. Simultaneously noise levels were also recorded. Subjective staff responses were gathered via the U.S. Army Research Lab-Specific Rating of Event Scale. A total of 33h of sound measurements showed that in multiple-bed patient rooms overall average sounds levels (Leq) were approximately 61dBA, and average sound levels during day (7am-7pm) and night (7pm-7am) were 6dBA and 59dBA, respectively. Three other noise measures considered in this study were Lmin, Lmax, Lpeak. Levels were 43dBA, 93dBA, 93-122dBC, respectively.

In another study, nurses working 8h evening shifts were significantly distressed by noise in two ICUs surveyed (Topf, 1989). It was also found that less sensitivity to noise and greater personality hardiness (such as commitment, control, and challenge) were linked with less noise-induced stress. This research did not collect any objective sound data but explored noise-induced subjective staff stress via personality hardiness measures and sensitivity to noise with the use of regression. Their sample size was 100 ICU nurses. Noise-induced stress data was collected via Disturbance Due to Hospital Noise Scale (DDHNS). Other results were collected via the Weinstein noise sensitivity scale, locus of control, work scale of alienation test, and security scale of California life goals evaluation schedule.

There is a very limited number of noise-induced nurse stress studies conducted in the ICUs. The following stress and annoyance studies are therefore included even though they are not conducted in the ICUs but in other sections of the hospital. In one study, enhanced reverberation time (RT) and speech intelligibility (SI) via acoustical interventions were related to improved perceived psychosocial work environment (such as low work demand, less strain, less pressure) (Blomkvist et al., 2005). The acoustical intervention consisted of adding sound absorbing ceiling tiles (renovated condition) in an 8-bed coronary care unit that originally had a sound reflective ceiling (base condition). Perceived psychosocial work environment data was collected repetitively before and after every 8h shift from 36 nurses in both the base and renovated conditions. Noise levels were also recorded during the two study periods, each of which lasted for 1 week. The staff perception was evaluated with multiple psychological factors (such as strain, tension, irritation, and anger) using a Demand, Control-Support Model. Analysis of variance (ANOVA) was used for the comparison of the data collected before and after the renovation. The SI and RT levels were measured in 3 private patient rooms and at the nurse station before and after the renovation. The RT levels improved from 0.8 s to 0.4sec at the nurse station and from 0.9s to 0.4s in the patient rooms after the design intervention. Overall average sound levels (Leq) were 57dBA and 56dBA at the nurse station and 56dBA and 50dBA in the patient room during the base and renovated conditions, respectively.

In another study, noise-induced annoyance was reported as a problem by the hospital staff (Bayo et al., 1995). In this study, descriptive statistics were used to describe noise-induced perceived staff outcomes more than causal relationships between objective sound levels and outcomes. Five- and 10-point scale surveys were used to measure perceived staff outcomes and loudness, respectively. Among the 300 staff members surveyed, 70% reported “very much” as the level of their annoyance due to noise. The other noise-induced outcomes were: work performance (13%), quality of work (13%), personal satisfaction (17%), and health (16%). Average perceived loudness was reported as 6.5 out of 10, with 10 being “very loud”. Leq, Ln percentiles, Lmin, and Lmax at different locations were measured based on 10min, 5min, and 1min sound measurements at 232 different locations inside the hospital on a regular floor (e.g., non-medical areas, corridors, clinics, operating theatre, wards, intensive care units) and at 121 locations outside the hospital (e.g., external premises and on the street). The Leq inside the hospital ranged between 52-75dBA, and outside the hospital between 52-82dBA. The measurements took place during morning (9am-1pm) and afternoon (4pm-8pm).

To summarize, there is some evidence that high noise levels in care settings contribute to staff stress and annoyance. However, the number of the studies specifically exploring the relationship between ICU noise levels on staff outcomes remains very limited.

Work Performance

Hospital sound environments that are supportive of hospital tasks could potentially improve staff effectiveness in delivering care. Improved nurse work performance in ICUs can prevent adverse events, improve healthcare quality, and optimize resource utilization. Studies of noise and hospital staff performance are quite limited, and some conflicting results are seen. Work performance in hospital noise studies has previously been assessed both quantitatively (i.e., mental efficacy, memory tests, and motion analysis systems) (Murthy et al., 1995) and qualitatively (i.e., blind observation) (Moorthy et al., 2004). Perceived noise-induced outcomes were typically assessed by self-report questionnaires (Ryherd et al., 2008). Sound environments have been characterized objectively in a variety of different ways (e.g., Leq, background noise levels, preferred speech interference levels, noise criteria, sound pattern, Ln percentiles, Lmax, Lmin, Lpeak, spectral qualities) (Hodge, & Thompson, 1990; Moorthy et al., 2004; Murthy et al., 1995; Ryherd et al., 2008).

One study found that noise in the workplace was perceived to have a negative impact on staff work performance (91%) and concentration (43%) (Ryherd et al., 2008). Perceived noise-induced outcomes were gathered from 47 nurses via 5-point scale questionnaire. Sound levels were measured continuously in a 2-bed patient room of a neurological-ICU during 5 week days. Different noise criteria methods (i.e., RC , RC Mark II, NC, NCB) were used to describe the sound quality of ICU noises. It was found that most ICU noises were hissy (excessive energy from 1-8 kHz). The study also considered the mean length of times when specific noise level conditions were met during the day and night times such as Lpeak <75dBA (6min, 8min respectively); Lmax<55dBA (10min, 8min respectively); and Leq<50dBA-restorative period (9min, 13min respectively). The overall average sound levels (ranged between Leq 53dBA-58dBA). Statistical level exceedances were also reported. It was found that 90% of the time the maximum and peak sound levels exceeded 50dBA and 70dBC, respectively.

A Neonatal-ICU study showed that sound that exceeds 55dBA most of the time can potentially interfere with work (Thomas, & Martin, 2000). This multidisciplinary literature review study highlighted that tasks requiring rapid reaction time and vigilance are sensitive to noise.

Noise-induced work performance research has been more commonly conducted in the operating theatres. For example, it was found that noise conditions with Leq of 77dBA were related to short term memory and decreased mental efficiency among twenty anesthesia residents (Murthy et al., 1995). The Trail Making Test, Digital Symbol Test, and Benton Visual Retentive Test were used for the assessment of cognitive tasks, mental efficacy, and short term memory. The performance tests were conducted in an acoustically treated room in which previously recorded operating room noise was played back. Overall Leq levels were recorded during 5 different types of operations in the operating room.

Another operating room study found that unpredictable and uncontrollable noise such as intermittent, intrusive noise (i.e., alarms >75-85dBA) can negatively affect performance and concentration during complex tasks (Hodge, & Thompson, 1990). This study pointed out that background conversation and peak sound levels (70-80dBA) can reduce the reliability of oral communication. In this study, only objective sound measurements were conducted and these results were interpreted with the literature reviewed. Based on the noise measurements conducted in the operating theatre, 50% of the time it was louder than 46dBA. The overall average Leq was 51dBA. Lpeak was 108dBA. Background noise level was 13dBA. Moreover to evaluate the reliability of the verbal communication, the Preferred Speech Interference (PSI) level (the arithmetic average of three octave bands centered at 500Hz, 1kHz and 2kHz) was compared with a commonly accepted value (noise levels between 47-52dB can be acceptable if the distance between speaker with normal-voice and talker does not exceed 6ft).

Conversely, Moorthy et al. (2004) found no difference in laparoscopic performance by surgeons under various noise/music conditions. This was potentially related with surgeons` ability to effectively "block out" interfering environmental conditions. However their ability to concentrate in noisy conditions can require too much effort. This study hypothesized that the complexity of the surgical tasks that require high concentration and skills moderate the effect of noise on a surgeon's performance. Three different acoustical conditions (music, noise and quiet) applied during 12 surgeries yielded no significant differences in the surgeons` performances. Sound levels were measured and recorded during 500-700min surgeries in the operating theatre. While surgeon performance was assessed by 2 blinded observers and validated motion analysis system, the noise recorded in the operating theatre played back continuously. Statistical significance tests and correlation analysis were used.

To summarize, the impact of noise on staff performance (especially in ICUs) has not been widely examined and the findings of the some of the previous studies are conflicting. Caregivers and patients can highly benefit from additional research to determine how the sound environment effects staff`s work performance in ICUs.

Health

The acoustic environment throughout the hospital may contribute to negative acute or chronic symptoms in staff. Critical care nursing is a very demanding job and it requires continuous alertness, vigilance, and well-being to conduct critical tasks effectively. One study found that of the 47 nurses surveyed in an ICU, 66% reported irritation and fatigue, while 40% reported headaches due to workplace noise (Ryherd et al., 2008). However, the impact of noise on surgeons` health in the operating theatres has been the primary focus of the previous literature examining noise and staff health. Due to the use of power instruments in operating rooms, medical staff members are commonly exposed to high noise levels. One review study suggested an association between surgeons hearing loss and 3 sound qualities of intensity, spectral frequency and pattern (i.e., intermittent, constant) (Thomas, & Martin, 2000).

Another study further examined the relationship between noise exposure levels and surgeon's hearing loss in the operating theatre during five surgeries (Love, 2003). Noise dosimeters were used to measure noise exposure levels during 2 knee replacement and 3 hip replacement surgeries conducted by 3 operating room surgeons. Leq levels varied between 75-82dBA. High Lpeak and Lmax levels were recorded at 140dB and 108dBA, respectively.

The association between high noise levels in the operating theatre and surgeons` noise-induced hearing loss was also suggested by Kracht et al. (2007). They recorded Leq noise levels as high as 66dBA in the operating theatre. They documented the noise levels during different surgeries such as neurology, urology, cardiology and gastrointestinal procedures. During the neuro-surgery, Lpeak exceeded 100dB over 40% of the time and 90dB over 95% of the time.

In addition to noise-induced hearing loss, the general health of staff is also a concern. However, very limited data in this area exists. One study showed that an increase in average sound levels was significantly related to an increase in heart rate, in addition to finding relationships between noise and perceived stress and annoyance as discussed above (Morrison et al., 2003) .

To summarize, there are agreed findings in the literature suggesting that surgeons' hearing health can be affected by high noise levels during surgery. Noise-induced hearing loss has particularly been a concern for surgeons in operating theatres. However, noise-induced health outcomes (including hearing loss) of ICU nurses` have not yet been the focus of previous research.

Work overload

When noise levels exceed a nurse's coping abilities it can lead to sensory overload (Baker, 1984). Sensory overload can cause emotional exhaustion, dissatisfaction, and decreased sense of personal accomplishment. This in turn can cause feelings of ineffectiveness, ineptitude, low satisfaction, and perceived lack of success (Barling, 2001). Laschinger and Leiter (2006) found that medication error and other adverse events necessary for patient safety were associated with emotional exhaustion.

Noise-induced stress due to ICU noise was positively related to nurse emotional exhaustion and burnout (Topf , &Dillon, 1988). It was found that ICU nurses who rotated shifts underwent more emotional exhaustion. Moreover during different shifts, nurses reported different levels of emotional exhaustion. A regression method was used to analyze the impact of covariates (i.e., sensitivity to noise, age, experience) and noise levels on nurse burnout, emotional exhaustion, and shift. Nurse responses were gathered via different surveys: the DDHNS for noise induced disturbance, Jones's Staff Burnout Scale Health Profession (SBS-HP) for burnout, Maslach`s Burnout Inventory for emotional exhaustion, Weinstein's noise sensitivity, and a life event stress and nursing stress survey. The study subjects were 100 critical care nurses from two hospitals that specialized in different areas (i.e., cardiac, medical-surgical, urology, neonatal, pediatric).

Reduced reverberation time and enhanced speech intelligibility via acoustical interventions in an intensive coronary unit was found to improve perceived staff attitude (Hagerman et al., 2005). Perceived staff attitude was collected via a 10-point scale questionnaire. After the application of sound absorbent materials, noise levels in the patient rooms dropped 5-6dB, but not at the nurse station. Reverberation time reduced from 0.9s to 0.4s in the patient rooms and from 0.8s to 0.4s at the nurse station. Measurements were conducted during the weekdays in relation to the changes in staffing during weekends. Speech intelligibility was measured in two different ways: RASTI and staff self-report. Non-parametric significance tests were used to compare the changes between different acoustic conditions.

To summarize, minimizing work overload is critically important for quality of care, patient safety, and the overall well-being of staff. Poor acoustical conditions in workplaces can aggravate staff attitude and perceived work overload. The limited existing evidence points to a significant problem that should be investigated further to determine appropriate acoustic conditions that will minimize negative work overload effects.

2.1.5 Medical alarms as noise sources and their effects

Caregivers continuously monitor auditory cues and respond to them immediately to keep patients safe. Clinical alarms are one of the key auditory cues in care settings. They are intentionally designed to sound highly dangerous, frightening, unpleasant, loud, and tense (Kuwano et al., 2001) because they have to be clearly distinguishable and alerting. Regardless their importance for patient safety, caregivers may find these sounds highly interrupting, annoying and overloading. The following section overviews the previous literature linking clinical alarms and caregiver outcomes.

Work performance

Frequently occurring excessive number of loud alarms can be problematic for nurse work performance. Currently available monitoring systems are able to monitor most physiological parameters (Chambrin, 2001). Each medical device emits multiple alarms with different acoustic qualities. However there is a limit to the amount of information that human auditory systems can process. Cropp et al. (1994) conducted listening tests in a critical care setting and found that excessive numbers of alarms confuse nurses (especially less experienced ones) and potentially affect their auditory monitoring performance. When nurses were presented previously recorded clinical alarms, they were able to correctly identify only half of the critical alarms. Wallace et al. (1994) also found the presence of similar clinical alarm detection difficulties in the operating rooms. Another study highlighted the waste of valuable staff time and delayed response time to a highly urgent condition related with difficulties during the detection of alarms - particularly high pitch tones (Meredith, & Edworthy, 1995). In particular caregivers with unilateral hearing loss can experience more difficulty in localization and discrimination of clinical alarms (Newby, 1979). Non-hospital research also indicated the difficulties of learning and remembering the significance of more than 8 different sounds even in unstressed conditions (Patterson, & Mikoy, 1980).

Alarms providing false information (a.k.a. false alarms) can also be problematic for nurse work performance. Nurses continuously asses all audible signals occurring in care settings as any auditory cue that might be clinically significant. However, false alarms and/or improper alarm settings cause unnecessary interruptions in the nurse work flow.

They also potentially lead to misconceptions and create a “cry wolf” environment where nurses ignore or inappropriately inactivate alarm signals (ECRI, 2007). A study found that only 10 of the 33 alarms were critical suggesting a serious problem with either patient or equipment (Cropp et al., 1994). As a result, false alarms are the indicators of inefficient patient monitoring systems (ECRI, 2006).

Health

Excessively loud alarms can potentially cause health problems among patients and caregivers. Kahn (1998) reported that noise sources in critical care settings with peak levels higher than 80dBA are amenable to behavior modification among staff members. Another study indicated that loud alarms can aggravate the rest of the staff members (Hedley-Whyte, 1988). Additionally, it has been found that a considerable percentage of nurses potentially experience sleep problems after an intensive work day with many alarms (Ryherd et al., 2008). In addition to behavioral consequences, exposure to high noise levels can lead to hearing disorders and often caregivers might not be aware of such significant health problems. For example, a study reported 37% of the physicians working in critical care settings were unaware of their hearing disorder (Wallace et al., 1994).

Annoyance, Disturbance and Anxiety

Disturbance by false alarms is commonly reported by nurses. Alarms that are not signaling a medical emergency can cause staff irritation and annoyance (Meredith, & Edworthy, 1995). A false alarm indicates a violated parameter of a vital sign that has no clinical consequence/ significance (Kerr, & Hayes, 1983). Lawless (1994) surveyed 2176 alarms and found 68% of them were false. Chambrin (2001) found only 5.9% of 3166 alarms required phone call to the physician.

Not only false alarms but noxious and repetitive signals are perceived as bothersome by caregivers (Chambrin, 2001; Schmidth, & Baysinger, 1986). Parallel with staff perceptions, patients also perceived clinical alarms as irritating, disturbing and frightening (Gast, & Baker, 1989; Kerr, &Hayes, 1983). According to SCCM, less noxious alarms can be provided by the modulation of critical alarms without reducing the importance or sense of urgency (SCCM, 1995).

Clinical alarms can also increase the anxiety levels of the occupants. One of the key responsibilities of the caregivers is to provide immediate response to alerting equipment that potentially poses a risk to patient safety. Difficulties in determining the location of the alarms delay caregiver response time to an alarm which in turn leads to increased anxiety in staff (Samuels, 1986). Parallel to caregiver experiences, patients also experience increased anxiety levels when they have difficulties in distinguishing between the alarms of alerting equipment as any alarming signal might pose a risk to their health condition (Kerr, & Hayes, 1983).

2.2 EMPIRICAL STUDY 1

CHARACTERIZING SOUND ENVIRONMENTS OF ICUS

2.2.1 Scope

Intensive care units (ICUs) have important but challenging sound environments. Alarms and equipment generate high levels of noise and ICUs are typically designed with hard surfaces that reflect sound. A poor sound environment can add to stress and make auditory tasks more difficult for clinicians. In particular, the Intensive Care Unit (ICU) sound environment is aurally demanding. Nurses often execute complex tasks in caring for critically ill patients and it is important to understand the subjective and objective qualities of the ICU sound environments from the nurses` point of view. However, few studies have linked detailed analyses of the ICU acoustical environment to the corresponding reaction of staff members.

In this study, subjective perception evaluations are coupled with objective sound level measurements to gain a more thorough grasp of how perceptual and physical acoustic parameters interact in the ICU setting. The subjective and objective qualities of two ICU environments with different design features are compared at multiple locations within each ICU. Specifically, the study aims to determine whether *objective noise levels* and *subjective perceptions* differed:

(a) between various locations within an individual ICU;

(b) when comparing similar locations in the two ICU's;

(c) when comparing overall (average) levels in the two ICU's to each other;

Additionally, relationship between objective and subjective noise levels was examined, including noise-induced nurse outcomes.

2.2.2 Methodology

The research is conducted in two intensive care units at Emory University Hospital: MedSurg-ICU and Neuro-ICU. Detailed information about the physical design qualities of these two settings can be found in Appendix B.

Both ICUs apply similar staffing models using intensivists and nurse practitioners and accommodate critical care patients with similar acuity levels. In both units, 10 to 12 registered nurses are typically working during each shift. The Neuro-ICU nurses mostly work 12h shifts (7am-7pm, 7pm-7am); the MedSurg-ICU nurses work both 12h and 8h shifts (7am-3pm, 3pm-11pm, and 11pm-7am). In both units, nurses can work weekend, weekday, or combination shifts, in addition to day, night, or combination shifts.

Objective noise measurements

Objective noise level measurements are conducted at 4 different locations in each unit: (a) centralized nurse station, (b) unoccupied patient room with the door closed, (c) occupied patient rooms with and without a respiratory ventilator, with the door continually opening and closing to accommodate patient care, and (d) multiple data points in the corridors. A total of 96h of samples are collected at the nurse stations in each unit from Thursday to Monday. Saturday and Sunday is intentionally included as these days have not typically been included in previous work.

In both units, patients with respiratory failure are connected to respiratory ventilator and most of those patients are critically ill which restricts the entries into the patient rooms. Due to this limited access, 45min samples are collected from the occupied patient rooms with a respiratory ventilator. It is possible to conduct longer measurements in the patient room without respiratory ventilator. In each unit, 24h continuous stationary sound level measurements are conducted in the occupied patient rooms without a respiratory ventilator during a weekday. Additionally, 45min samples are collected in an empty patient room while patient room doors are closed. At the corridors, multiple 15min sound samples are collected at randomly selected times during day and night. In total, approximately 246h of sound data are collected from both units. For the calculation of overall noise levels in each unit, all sound data collected at different locations are taken into consideration. Noise levels in the two ICUs are generated by different types of sources. Medical equipment alarms occurring in the patient rooms, patient monitor alarms occurring both in the patient rooms and at the nurse stations, sound of the ice machine, phone ringing, staff conversation, and rolling medical carts in the corridors are some of the common noises in two units. In the MedSurg-ICU, nurses are paged via overhead pagers. In the Neuro-ICU 3G-phones or regular phones at the alcoves are used instead.

At the corridors, the microphone is located at a height of approximately 1.4 m (4.5 ft) slightly off the room center and stabilized on a tripod. In the patient rooms, the microphone is hung from the ceiling at a height of approximately 1.8 m (6 ft) above finished floor. Similarly, the microphone is hung from the ceiling at the nurse stations at a height of approximately 1.8 m (6 ft) above finished floor. In the Neuro-ICU, the sound level meter is set up at the nurse station in the 14-bed cluster. In the MedSurg-ICU, the sound level meter is located at slightly off the center of the central nurse work zone in the center of the unit. All sound data is collected using a fast response time for equivalent, maximum and minimum levels (0.125 s) and one-minute averaging intervals. Three Larson Davis type 824 sound level meters and Larson Davis 824 Utility software is used. The dynamic range is 80 dB unweighted from 38 dB to 118 dB.

Subjective noise measurements

An electronic survey is administered to registered nurses working in the Neuro-ICU and MedSurg-ICU. The survey consists of 4 sections: nurse profile and working conditions, perceived sound environment in the workplace, perceived impact of noise levels on nurse outcomes, general hearing health and noise sensitivity. The survey is completed by 35 Neuro-ICU and 23 MedSurg-ICU nurses, corresponding to response rates of 39% and 35%, respectively. In the Neuro-ICU, 85% of the respondents are full-time and 15% part-time. In the MedSurg-ICU, 70% were full-time, 26% part–time, and 4% PRN (on-call nurse). In both units more than 80% of the respondents are female and more than 80% of were younger than fifty years old.

2.2.3 Findings

Objective noise levels

The noise levels measured at 4 different locations in each unit (nurse station, occupied and unoccupied patient rooms, and corridors) are averaged to find single number overall levels in each ICU. As shown in Figure 2.1, the overall averaged levels in the two units range from 57-58 dBA Leq, 97-105 dB LMax, 54-58 dB LMin, and 113-120 dBC LPeak. Given these values, the difference between overall averaged LAeq levels in the Neuro-ICU and MedSurg ICU are imperceptible.

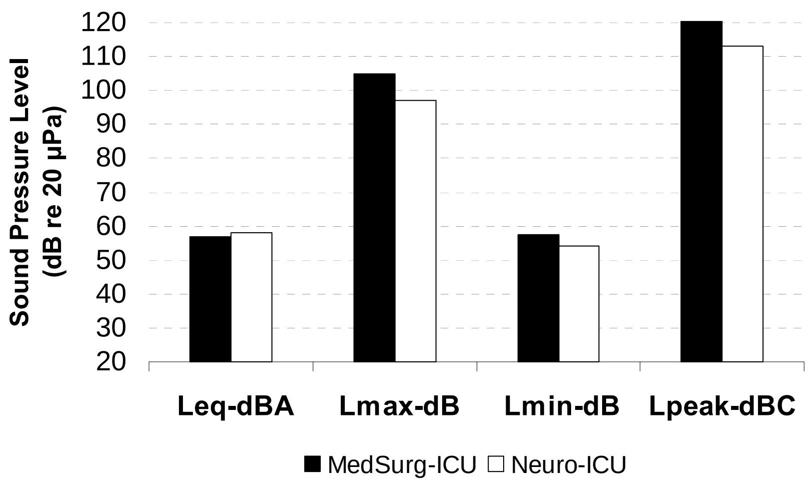


Figure 2.1 Overall LAeq, LMax, LMin and LPeak noise levels in the two ICU`s

Further analysis is shown in Figure 2.2, which presents the percentage of time that the maximum noise levels (LMax) exceeded values ranging from 70 to 90 dB. This type of analysis is referred as the "*occurrence rate*" in this study, and has been used successfully in previous hospital studies by the authors to analyze differences between day and night (Ryherd, Persson Waye, & Ljungkvist, 2008), in addition to related analyses by others

(Kracht, Busch-Vishniac, &West, 2007; MacKenzie, & Galbrun, 2007; Williams, Drongelen, & Lasky, 2007). In both units, LMax exceeds 70 dB more than 98% of the time and LPeak exceeds 80 dBC more than 96% of the time. Thus the difference in the occurrence rate of lower level transient sounds (<70 dB LMax and <80 dBC LPeak) and very high level transient sounds (>90 dB LMax and >100 dBC LPeak) in the two ICU's is negligible. However, a difference between the two wards emerges for mid-level transient sounds, as Figure 2.2 indicates. LMax exceeds 80 dB more of the time in the MedSurg-ICU than in the Neuro-ICU. Similarly, LPeak exceeds 90 dBC more of the time in the MedSurg-ICU than in the Neuro-ICU. This indicates that the MedSurg-ICU is a more impulsive sounding environment overall.

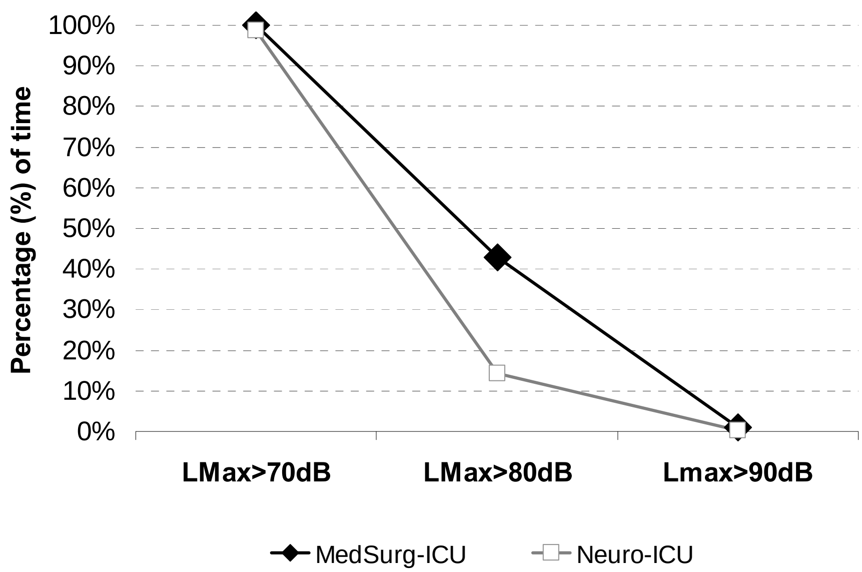


Figure 2.2 Occurrence rate of different LMax noise levels in the two ICU`s

To summarize, the sound environments of two ICU's are similar based on traditional measures of overall Leq, LMax, LMin, and LPeak, but are different based on the occurrence rate of mid-level transient sounds. Note that the terminology "mid-level transient sounds" does not refer to the perceived loudness of the transient level, but simply serves to distinguish the level ranges analyzed in this study into lower, mid, and higher regions.

The average noise levels measured at each of the four different locations (nurse station, occupied and unoccupied patient rooms, and corridors) are shown in Figure 2.3 for each ICU. The occupied patient rooms without respiratory ventilator are chosen for this analysis as there has been better access for longer measurements as compared to the patient rooms with respiratory ventilators as previously discussed. The overall averaged levels in the two ICU's range between 45-60 dBA Leq depending on the location. The unoccupied patient rooms are the quietest (45-52 dBA) and the nurse station, occupied patient rooms, and corridors have similar noise levels (56-60 dBA). It is observed that the differences between overall averaged LAeq levels for similar occupied locations in the Neuro-ICU and MedSurg ICU are imperceptible (e.g. the nurse stations in both units have similar Leq levels). However, the overall averaged LAeq is higher in the unoccupied patient rooms of the MedSurg-ICU compared to the Neuro-ICU. Similar trends are found for traditional measures of overall LMax, and LPeak in the two ICU's.

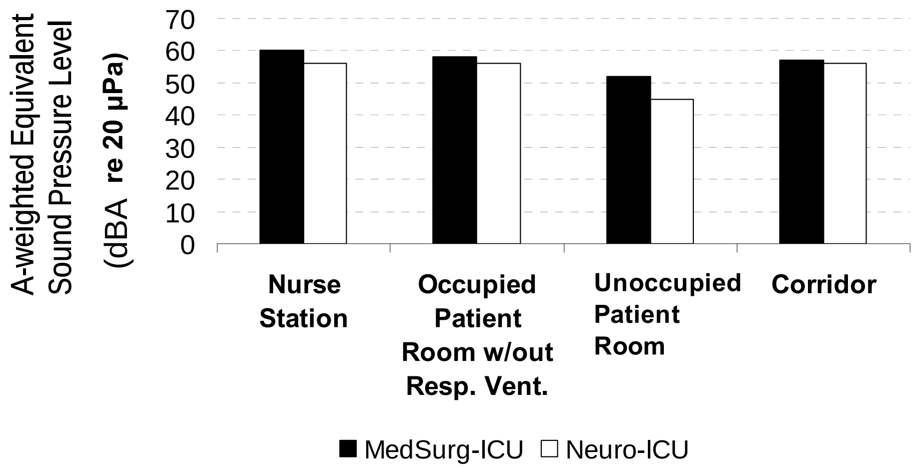


Figure 2.3 Overall A-weighted equivalent sound pressure levels (Leq in dBA) at different locations in the two ICUs

The occurrence rates of LMax and LPeak at each of the 4 locations in each ICU are also analyzed. At all 4 locations in both units, LMax exceeds 70dB more than 98% of the time and LPeak exceeds 80 dBC more than 94% of time. As before, a difference between the 4 spaces emerges for mid-level transient sounds, (Figure 2.4-Figure 2.6). For example, Figure 2.4 shows the central nurse station results, where LMax exceeds 80 dB more often in the MedSurg-ICU (43%) than in the Neuro-ICU (15%). Figure 2.5 and Figure 2.6 show similar analysis for all spaces in the two ICU's. The occupied spaces (nurse station, occupied patient rooms, and corridors) are more impulsive in the MedSurg-ICU (Figure 2.5) compared to the Neuro-ICU (Figure 2.6). The occurrence rates for the unoccupied patient rooms are similar in the two ICU's. LPeak occurrence rate analysis for the four spaces in both ICU's shows very similar results to LMax occurrence rate results.

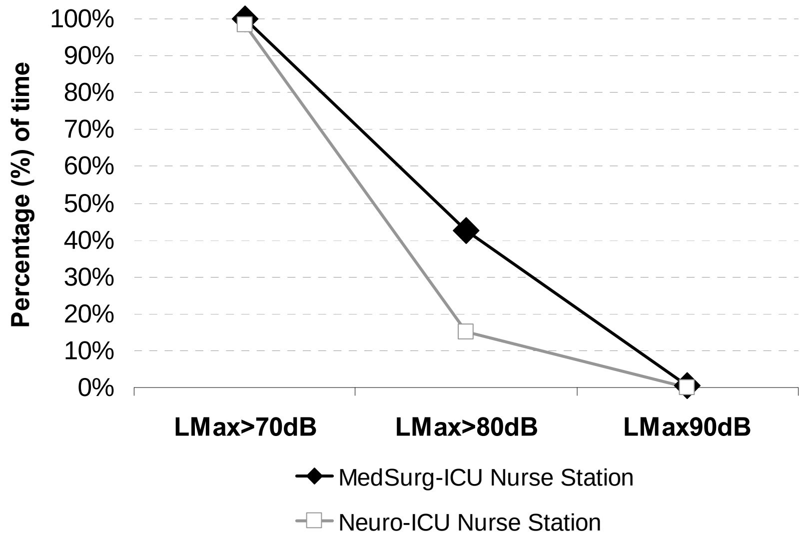


Figure 2.4 Occurrence rate of different LMax noise levels at the nurse stations

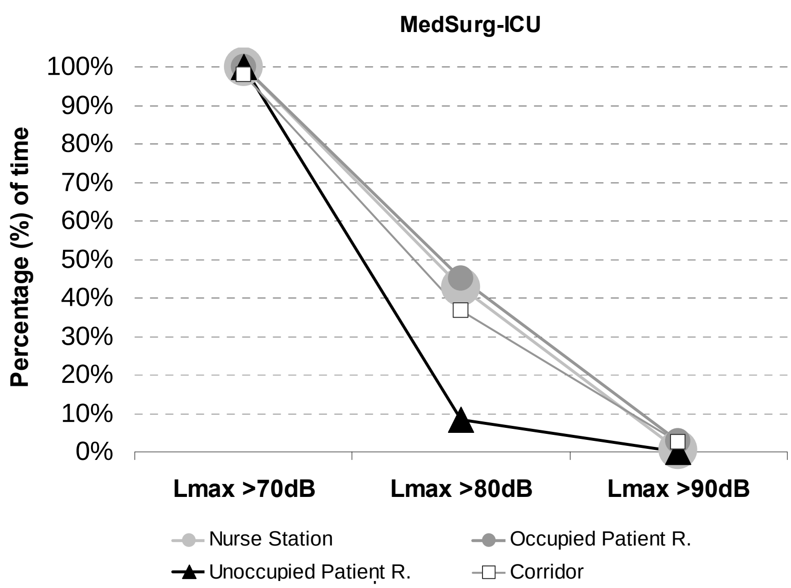


Figure 2.5 Occurrence rate of different LMax noise levels in the MedSurg-ICU

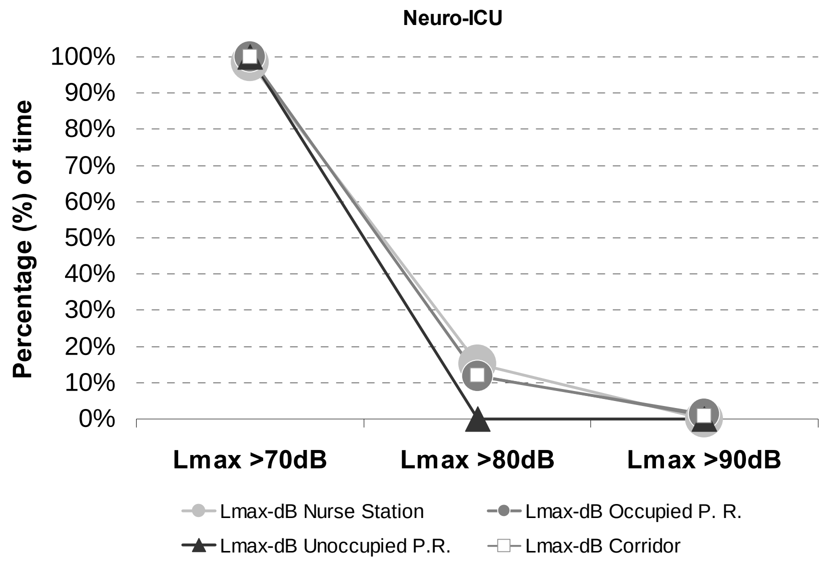


Figure 2.6 Occurrence rate of different LMax noise levels in the Neuro-ICU

Subjective Noise Perception

Does subjective perception differ when comparing two ICU's to each other?

Overall, the MedSurg-ICU sound environment is perceived as significantly worse for nurse wellbeing and work performance as compared to the Neuro-ICU sound environment. Results for 5 nurse outcomes are shown in Table 2.1: perceived loudness, annoyance, work performance, general health outcomes, and anxiety. A discrete 5-point rating scale is used in for all 5 outcomes shown. Workplace noise is perceived as louder, more annoying, and having a greater negative impact on work performance, health outcomes, and anxiety by the MedSurg-ICU nurses compared to the Neuro-ICU nurses. The nurses` sensitivity to noise and tolerance to high noise levels in the workplace does not differ significantly between ICU's ($p<0.05$). Overall, the nurses in both units have rated themselves as not very sensitive to noise and thought they can somewhat tolerate high noise levels. Perceived hearing ability of two unit nurses also does not differ significantly, and has been rated as “good” on average in both units.

Table 2.1 (a) Mean perception ratings of noise-induced nurse outcomes in the two ICUs (b) distribution of noise-induced nurse outcomes in the two ICUs

Neuro-ICU *(1: completely disagree; 5: completely agree)*	MedSurg-ICU *(1: completely disagree; 5: completely agree)*	Nurse outcomes	
3.0 ⟷	4.3**	Loudess	*My workplace is very loud.*
3.0 ⟷	3.9*	Annoyance	*I find the noise very annoying in my workplace.*
1.9 ⟷	3.0*	Performance	*The noise in my workplace negatively affects my work performance.*
1.7 ⟷	3.0**	Health	*The noise in my workplace negatively affects my health.*
2.0 ⟷	3.9**	Anxiety	*The noise in my workplace increases my anxiety levels.*

* The mean perception rating is significantly higher at 0.05 level ($p<0.05$).
** The mean perception rating is significantly higher at 0.01 level ($p<0.01$).

	5-point scale	Loudness	Noise-induced annoyance	Noise-induced work perf.	Noise-induced health	Noise-induced anxiety
Neuro-ICU	*Completely disagree-1*	23.0%	20.0%	48.6%	60.0%	51.4%
	Somewhat disagree-2	14.2%	11.4%	22.8%	20.0%	20.0%
	Neither agree nor disagree-3	17.1%	25.7%	17.1%	14.3%	2.9%
	Somewhat agree-4	34.3%	34.3%	8.6%	2.8%	22.8%
	Completely agree-5	11.4%	8.6%	2.9%	2.9%	2.9%
MedSurg-ICU	*Completely disagree-1*	0.0%	4.3%	20.4%	21.7%	13.0%
	Somewhat disagree-2	8.7%	8.7%	26.1%	26.1%	0.0%
	Neither agree nor disagree-3	4.3%	13.0%	17.4%	13.0%	17.4%
	Somewhat agree-4	34.8%	43.5%	26.1%	4.3%	26.1%
	Completely agree-5	52.2%	30.4%	14.0%	34.8%	43.5%

Does subjective perception differ when comparing similar locations in the two ICU's to each other and within an ICU?

Though not all results are statistically significant, the trend is that the noise is consistently perceived as louder and more annoying at all 4 locations (nurse station, occupied and unoccupied patient rooms, and corridors) in the MedSurg-ICU as compared to the Neuro-ICU. Results are shown in Table 2.2. A discrete 5-point rating scale is used in for loudness and annoyance perception. Nonparametric Mann-Whitney U test results show that the differences for the nurse stations and in the empty patient rooms are statistically significant at (p<0.05 or p<0.01).

Table 2.2 Mean perception ratings of loudness and annoyance at different locations in the two ICUs

	Noise-induced annoyance		Loudness	
	MedSurg-ICU	Neuro-ICU	MedSurg-ICU	Neuro-ICU
Nurse Station	3.8* ↔	2.9	4.1* ↔	3.2
Unoccupied Patient Room	2.25* ↔	1.6	2.7** ↔	1.8
Occupied Patient Room	3.0 ↔	2.6	3.4 ↔	3.1
Corridor	2.8 ↔	2.7	3.3 ↔	2.9

* The mean perception rating is significantly higher at 0.05 level (p <0.05).

** The mean perception rating is significantly higher at 0.01 level (p <0.01).

Differences in perception between 4 locations within each individual ICU are also found based on the values in Table 2.2. In the MedSurg-ICU, the nurse station is perceived as significantly louder than other three locations ($p<0.05$). In the Neuro-ICU, the empty patient room is perceived as significantly quieter and less annoying than the other three locations ($p<0.05$).

Correlations between Objective and Subjective Measures

Spearman nonparametric correlation tests are used to analyze the relationships between objective noise levels and subjective loudness and annoyance perception. As shown in Table 2.3, subjective annoyance and loudness perception is significantly and positively correlated with Leq (dBA) in both ICU's. The interpretation is that the nurses perceive the noise as more annoying and louder as the Leq increases. Additionally, the mid-level transient sounds (LMax>80 dB and LPeak>90 dBC) are significantly related to annoyance and loudness perception (Table 2.3). Nurses perceive noise as more annoying and louder the more often (higher % of time) LMax exceeds 80 dB or LPeak exceeds 90 dBC.

Table 2.3 Correlations between objective noise levels (i.e., Leq, LMax and LPeak occurrence rates) and subjective perception of annoyance and loudness

	Noise levels	ANNOYANCE	LOUDNESS
Neuro -ICU	Leq (dBA)	0.36**	0.41**
	LMax> 80dB	0.35**	0.39**
	LPeak> 90dBC	0.35**	0.40**
MedSurg -ICU	Leq (dBA)	0.38**	0.42**
	LMax> 80dB	0.25*	0.26*
	LPeak> 90dBC	0.35**	0.41**
Overall (two units)	Leq (dBA)	0.38**	0.44**
	LMax> 80dB	0.38**	0.43**
	LPeak> 90dBC	0.38**	0.45**

* Correlation is significant at 0.05 level ($p < 0.05$)
** Correlation is significant at 0.01 level ($p < 0.01$)

Spectral content

The frequency distribution of noise levels for the two ICU's are shown in Figure 2.7 and Figure 2.8. Similar trends in frequency content are seen for the 4 locations within each individual ICU, with the unoccupied patient room generally quieter than the occupied spaces.

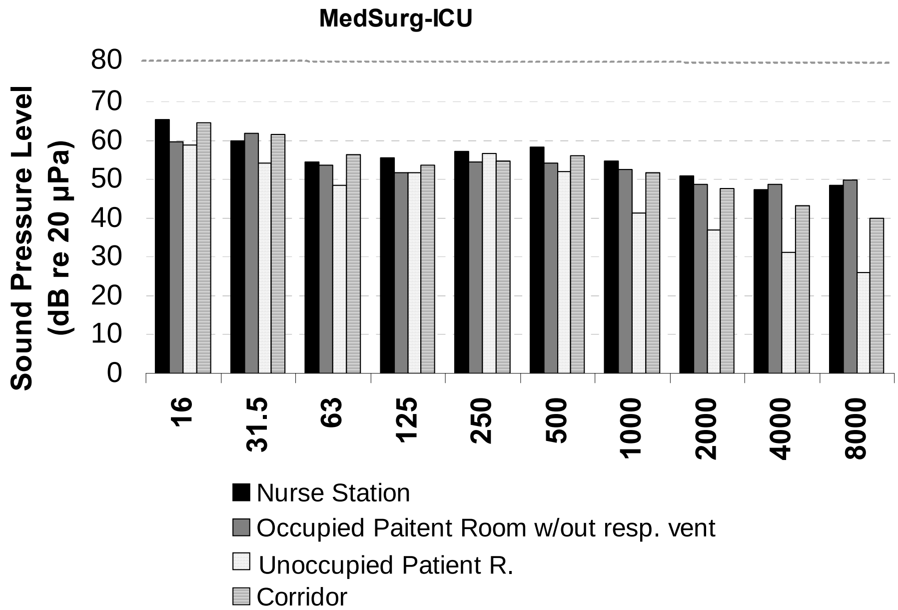


Figure 2.7 Average sound pressure levels across frequency in the MedSurg-ICU

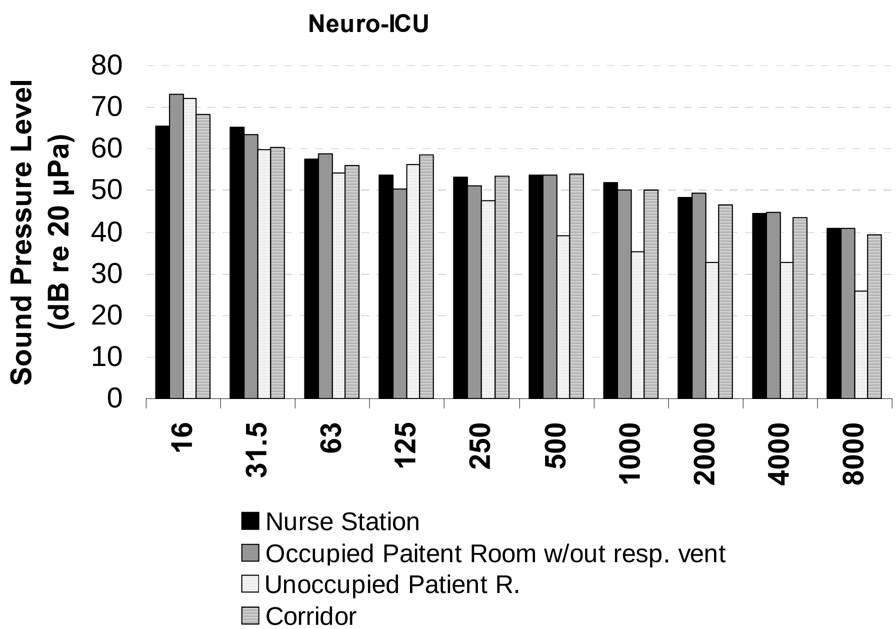


Figure 2.8 Average sound pressure levels across frequency in the Neuro-ICU

When comparing the two ICU's to each other, the sound pressure levels are generally somewhat higher in MedSurg-ICU, particularly from 250 Hz-8 kHz. At 8 kHz, clearly noticeable noise level differences have occurred between two ICU's nurse stations and occupied patient rooms (e.g., at 8kHz Neuro-ICU nurse station=41dB; MedSurg-ICU nurse station=49dB). At 250 Hz and 500 Hz, clearly noticeable noise level differences have occurred between the empty patient rooms in the two wards (e.g., at 500Hz Neuro-ICU= 40dBA; MedSurg-ICU=51dB). The differences between ICU's above 250 Hz are likely related to increased noise from occupants, alarms, and airflow from ventilation systems in the MedSurg-ICU. Below 250 Hz, sound levels are generally somewhat higher in the Neuro-ICU. In the empty and occupied patient room, noise level differences between the MedSurg-ICU and Neuro-ICU at 16 Hz are clearly noticeable. The difference between the ICU's at low frequencies may be related to noise from HVAC equipment located near the center of the Neuro-ICU. The equipment is located in an outdoor space that is not accessible by the occupants but included in the design to provide natural light for some patient rooms.

Noise Fluctuations

The traditional fluctuation metric of (L_{10} - L_{90}) does not have sufficient range to capture the noise fluctuation differences in two ICU`s and at different locations in each ICU. At all measurement locations, L_{33} results are consistently within 1 dB of non-weighted Leq results. However, noise fluctuations calculated based on the differences between maximum and averaged sound pressure levels (LMax minus Leq); and peak and averaged sound pressure levels (LPeak minus Leq) are effective in capturing the noise fluctuation differences. Overall, noise fluctuations are higher in the MedSurg-ICU compared to the Neuro-ICU as shown in Figure 2.9. The interpretation is that the MedSurg-ICU nurses are exposed to more dramatic noise level changes compared to the Neuro-ICU nurses. This result is consistent with the significant differences between nurse outcomes and subjective loudness and annoyance levels in the two ICUs. Figure 2.9 also shows the consistency between the noise fluctuation trends and the trend generated by annoyance and loudness perception of nurses in the two ICUs.

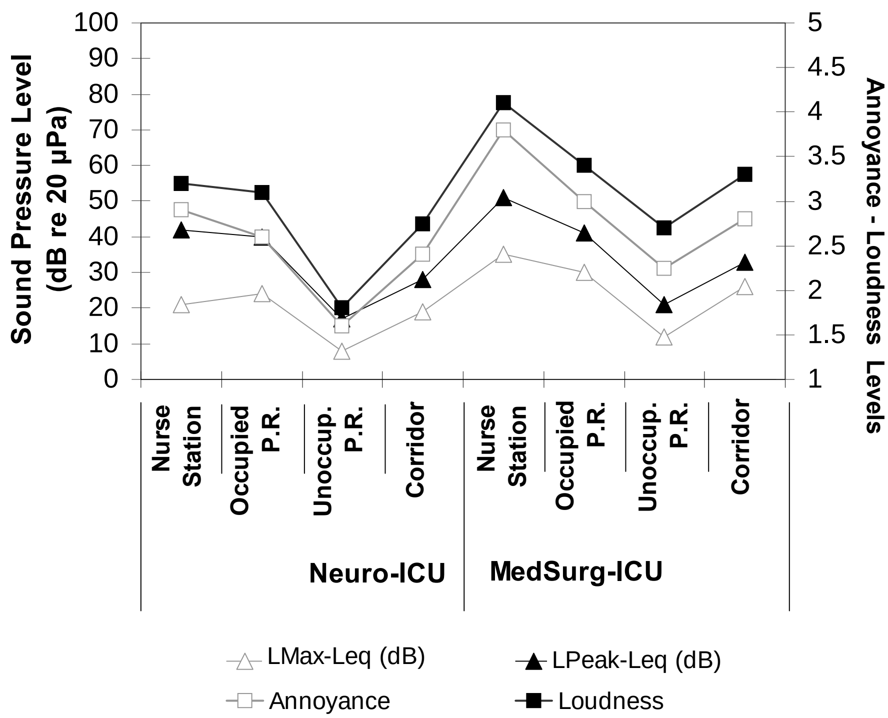


Figure 2.9 Non-weighted noise fluctuation levels (*calculated based on noise level differences between LMax -Leq and LPeak -Leq*), annoyance and loudness levels

Speech Interference Levels

The potential for the background noise to interfere with speech communication, or "speech interference level (SIL)" is also evaluated, as shown in Table 2.4. The SIL is calculated as the arithmetic average of octave band sound pressure levels from 500Hz to 4kHz, with a higher SIL indicating more potential for interference (Mehta, Johnson, & Rocafort, 1999). In general, the SIL's in the MedSurg-ICU are slightly higher at all 4 locations compared to the Neuro-ICU. The SIL is highest at the nurse stations, ranging from 50-53 dB. At this level, two female nurses will be able to (barely) communicate with each other in normal voice up to a distance of nearly 0.9m-1.2 m (3ft-4 ft). The distance would increase to 1.6m-2.3 m (5.5ft-7.5 ft) if the nurses raise their voices (Mehta, Johnson, & Rocafort, 1999). Lower SIL levels can enable safer communications from longer distances. Moreover, compared to females, males in general are able to communicate better at longer distances.

Table 2.4 Speech interference levels at different locations in two ICUs (also includes corresponding distances between speaker and listener for reliable communication during normal voice and raised voice usage)

	MedSurg-ICU			Neuro-ICU		
	SIL (dB)	Speaker-listener distance (ft)		SIL (dB)	Speaker-listener distance (ft)	
		Normal voice	Raised voice		Normal voice	Raised voice
Nurse Station	***53***	3.0	5.5	***50***	4.0	7.5
Occupied Patient Room	***51***	3.5	6.5	***49***	4.5	9.0
Unoccupied Patient Room	***40***	12.0	23.5	***35***	21.5	43.0
Corridor	***50***	4.0	7.5	***49***	4.5	9.0

SIL: Speech interference level

2.2.4 Discussion

This study discussed objective and subjective characteristics of hospital sound environments in detail. Overall, the MedSurg-ICU is perceived as significantly louder, more annoying, and having a greater negative impact of noise on work performance, health outcomes, and anxiety as compared to the Neuro-ICU. Additionally, the noise is consistently perceived as louder and more annoying at the all four locations (nurse station, occupied and unoccupied patient rooms, and corridors) in the MedSurg-ICU as compared to the Neuro-ICU. However, the nurses` loudness and annoyance perceptions significantly differed only at the nurse station and in the unoccupied patient room. Surprisingly, there is little difference between the sound environments of the two ICU’s based on traditional overall measures of Leq, LMin, and LMax, and LPeak, particularly for occupied spaces. The objective differences between the occupied sound environments in the two wards only emerges through a more comprehensive analysis of the occurrence rate, frequency content, and the speech interference level. Further, perceived annoyance and loudness levels are significantly and positively correlated to mid-level transient sound occurrence rates. This indicates that the traditional overall noise measures may be inadequate to capture the differences in perception between hospital sound environments.

Interesting differences are also found when comparing similar locations (nurse station, occupied and unoccupied patient rooms and corridors) within each individual ICU. Specifically, the MedSurg-ICU nurse station is perceived as significantly louder than other locations within that ICU and the Neuro-ICU unoccupied patient room is perceived as significantly quieter and less annoying than other locations within that ICU. Nurse stations are highly transient sound environments where sound sources include medical alarms, telephone ringing, staff talking and laughing, footfall noise, etc. Unlike nurse stations, empty patient rooms with the doors closed have more stationary sound environments where the main noise source is the HVAC system. In highly transient sound environments such as nurse stations, differences in perception are likely more related to differences in the occurrence rate of maximum and peak levels. On the other hand, in more stationary sound environments such as unoccupied patient rooms the differences in subjective perception are likely more related to differences between overall equivalent levels (Leq).

By comparing the objective noise measures and subjective perception between the two ICU's and at four locations within each ICU, an interesting conclusion regarding noise measures emerges. One must consider the overall equivalent level (Leq) or some related measure of loudness in addition to the occurrence rate, or some related measure of the transient nature of the sound. The perception of unoccupied spaces (such as empty patient rooms) will likely be more related to the overall level, while the perception of occupied spaces (such as nurse stations) will likely be more related to the transient nature of the sound. The frequency content and SIL (or related speech measures) should also be considered.

2.3 EMPIRICAL STUDY 2

TIME-BASED VARIATIONS OF HOSPITAL NOISE

2.3.1 Scope

The study discussed in the previous section compared two critical care sound environments objectively and subjectively. One of the ICUs is perceived as louder, more annoying, and having a greater negative impact of noise on work performance, health outcomes, and anxiety. Surprisingly, there is little difference between two ICU sound environments based on traditional overall noise measures. The objective differences between the occupied sound environments in the two units only emerges through a more comprehensive analysis of the "occurrence rate" of peak and maximum levels, frequency content, and the speech interference level. To assess the effectiveness of the new acoustic metric, "occurrence rate", a follow up empirical study is conducted. The second study is also important to assess the behavior of sound over time in the two critical care settings.

2.3.2 Methodology

Subjective noise levels

Two additional sets of subjective noise level analyses are conducted by using the data collected in the previous empirical study: a) weekday vs. weekend, and b) day vs. night vs. shift changes. In addition to the components already discussed, the online survey also includes questions about noise-induced annoyance and loudness levels during different times of the day and different days of the week. Details of the methodology are shown in section 2.2.2.

Objective noise levels

Two additional sets of objective noise level analyses are conducted by using the data from the previous empirical study: a) weekday vs. weekend, and b) day vs. night vs. shift changes. As previously described in section 2.2.2, 96 h of sound data has been collected at the central nurse stations of the two ICUs (see Figure 2.10 and Figure 2.11 for nurse station locations and layouts). In addition to weekdays, noise level measurements are intentionally conducted during the weekend as these days have not been typically included in the previous work. Noise level measurements have taken place at the nurse stations from Thursday to Monday. Sound data collected during the three weekdays (Thursday-Friday and Monday), and at the weekend (Saturday and Sunday) are analyzed separately. For the calculation of overall noise levels in each ward, all sound data collected from Thursday to Monday are averaged. In the second analysis, noise levels during the day, night and shift times are analyzed separately. Day and night times are defined based on 12h nurse shift in the Neuro-ICU (7am-7pm and 7pm-7am) and 8h nurse shift in the MedSurg-ICU (7am-3pm, 3pm-10pm and 10pm-7am). In two wards, nurse shift changes continue about 45-60min after and start 20-25min before the shift.

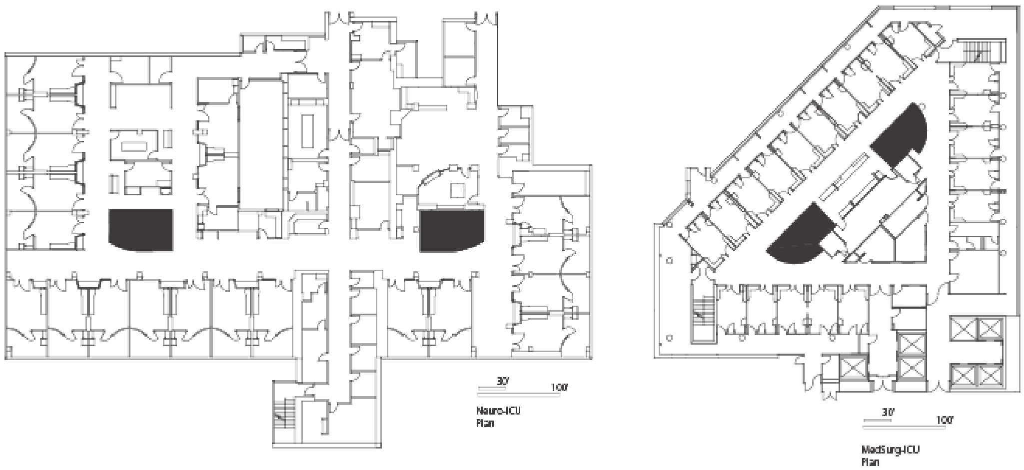


Figure 2.10 Floor plans of two ICU`s showing the distribution of nurse stations
(left) Neuro-ICU; (right) MedSurg-ICU

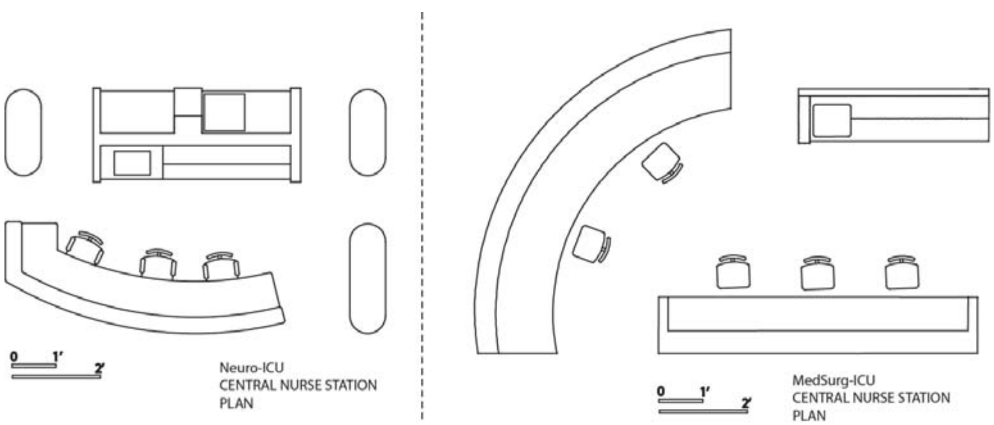


Figure 2.11 Floor-plans of nurse stations in the two ICU`s
(left) Neuro-ICU; (right) MedSurg-ICU

2.3.3 Findings

Subjective noise levels

Subjective noise level during the weekdays and at the weekend

The first set of subjective noise level analysis is conducted to assess MedSurg-ICU and Neuro-ICU nurses` annoyance and loudness perceptions for weekdays vs. weekends. Results are shown in Table 2.5. A discrete 5-point rating scale was used for noise-induced annoyance and loudness perception. Nonparametric Mann Whitney U test is used to analyze the significant differences between the perceptions of nurses in the two units. Compared to Neuro-ICU, the MedSurg-ICU is perceived as louder and more annoying both during the weekdays and the weekend. However, statistically significant differences between loudness and annoyance perceptions of the nurses in the two units have occurred only during the weekdays. Overall, Neuro-ICU nurses` loudness and annoyance perceptions do not vary much when comparing weekday to weekends. However, the trend is that MedSurg-ICU nurses found weekends quieter and less annoying compared to weekdays.

Table 2.5 (a) Annoyance and loudness perceptions for weekdays vs. weekend (b) distribution of nurse annoyance and loudness perceptions in the two ICUs

	Annoyance		Loudness	
	Weekday	Weekend	Weekday	Weekend
Neuro-ICU	3.2	3.0	3.2	3.1
MedSurg-ICU	4.0*	3.2	3.9*	3.3

* The mean perception rating is significantly higher at 0.05 level ($p<0.05$)
** The mean perception rating is significantly higher at 0.01 level ($p<0.01$)

Table 2.5 continued

5-point scale		Annoyance		Loudness	
		Weekday	Weekend	Weekday	Weekend
Neuro-ICU	*Completely disagree-1*	25.3%	8.6%	15.0%	10.3%
	Somewhat disagree-2	18.4%	8.6%	20.5%	10.3%
	Neither agree nor disagree-3	17.1%	15.4%	14.3%	18.0%
	Somewhat agree-4	22.0%	21.0%	24.0%	25.0%
	Completely agree-5	24.0%	28.0%	25.0%	26.0%
MedSurg-ICU	*Completely disagree-1*	4.0%	17.4%	0.0%	10.0%
	Somewhat disagree-2	4.3%	4.3%	4.3%	8.0%
	Neither agree nor disagree-3	8.7%	26.1%	8.7%	26.1%
	Somewhat agree-4	43.0%	24.0%	39.0%	30.0%
	Completely agree-5	39.0%	25.0%	40.0%	22.0%

Subjective noise level during the day and night times and shift change

The second set of subjective noise level analysis is conducted to assess Neuro-ICU and MedSurg-ICU nurses` noise level perceptions during different times of the day. Two unit nurses are asked to rate their annoyance and loudness perceptions during the day times, night times, and shift changes. According to Mann Whitney nonparametric significance test results, the MedSurg-ICU is consistently perceived to be more annoying and louder during certain times of the day compared to Neuro-ICU (Table 2.6). Although the trend is that the MedSurg-ICU is perceived worse during all times, statistically significant differences occurred only during the day times and shift changes. Additionally, the trend is that in both units nurses generally has found noise levels slightly more annoying during the shift changes compared to day and night times. However, their loudness perceptions during the day times and shift changes are very similar. The trend is that night times were perceived as less annoying and quieter in both units.

Table 2.6 Annoyance and loudness perceptions during different times of the day

	Loudness			Annoyance		
	Day	Night	Shift	Day	Night	Shift
Neuro-ICU	2.9	2.7	3.2	3.3	2.8	3.4
MedSurg-ICU	3.9*	3.3	4.2*	4.3*	3.4	4.3*

* The mean perception rating is significantly higher at 0.05 level ($p<0.05$)
** The mean perception rating is significantly higher at 0.01 level ($p<0.01$)

5-point scale		Annoyance			Loudness		
		day time	night time	shift time	day time	night time	shift time
Neuro-ICU	*Completely disagree-1*	18.6%	10.0%	8.6%	8.6%	11.4%	25.0%
	Somewhat disagree-2	17.1%	11.4%	17.1%	12.9%	11.4%	17.6%
	Neither agree nor disagree-3	20.0%	12.9%	14.3%	25.0%	13.0%	25.4%
	Somewhat agree-4	16.0%	20.0%	26.0%	27.0%	21.0%	23.2%
	Completely agree-5	22.0%	24.0%	27.0%	23.0%	25.0%	21.6%
MedSurg-ICU	*Completely disagree-1*	4.3%	13.0%	4.3%	0.0%	16.0%	0.0%
	Somewhat disagree-2	0.0%	15.0%	4.3%	0.0%	18.0%	4.3%
	Neither agree nor disagree-3	19.0%	18.0%	13.0%	21.7%	13.0%	17.4%
	Somewhat agree-4	28.0%	25.0%	34.0%	36.0%	25.0%	33.0%
	Completely agree-5	44.0%	27.0%	47.0%	45.0%	30.0%	48.0%

To summarize, subjective noise levels in each unit varied during different times of the day and different days of the week. The trend is that the MedSurg-ICU is consistently perceived worse. However statistically significant differences occurred only during the weekdays. Significant differences between nurse perceptions is also evident only during the day times and shift changes.

Objective noise levels

Noise levels during the weekdays and at the weekend

The first set of objective noise level analysis is conducted to assess the differences between the two ICU sound environments and occurring in each unit during the weekdays and the weekend. Related with the scope of this study, noise levels in the two ICUs are analyzed via "occurrence rate" analysis.

The overall averaged sound pressure levels (Leq) at the nurse stations of two units range between 57-60dBA and 56-58dBA during the weekdays and at the weekend respectively. Given these results, the difference between two wards during different days of the week is imperceptible (Mehta et al., 1997).

As shown in Figure 2.12-Figure 2.16, occurrence rate values present the percentage of time that the peak noise levels exceeded values ranging from 80dBC to 100dBC. In both units, Lpeak noise levels exceed 80dBC more than 95% of the time during the weekdays and at the weekend. The occurrence rate of Lpeak noise levels exceeding 100dBC is negligible in both units during the weekdays and at the weekend. On the other hand, as shown in Figure 2.12, substantial differences between the two wards emerge for mid-level Lpeak noise levels during the weekdays. As noted in earlier sections, the terminology for "mid-level" for 90dBC does not refer to the perceived loudness of the transient level, but simply serves to distinguish the level ranges analyzed in this study into lower, mid and higher regions. In the MedSurg-ICU, Lpeak noise levels exceed 90dBC more of the time than in the Neuro-ICU during the weekdays. The difference between the two units is much more evident during the weekdays as compared to the weekend. Similar results are also found for Lmax levels. To summarize, although there is not a difference in overall levels (LAeq), the occurrence rate analysis indicate that the

MedSurg-ICU is a more impulsive sounding environment compared to Neuro-ICU, particularly during the weekdays.

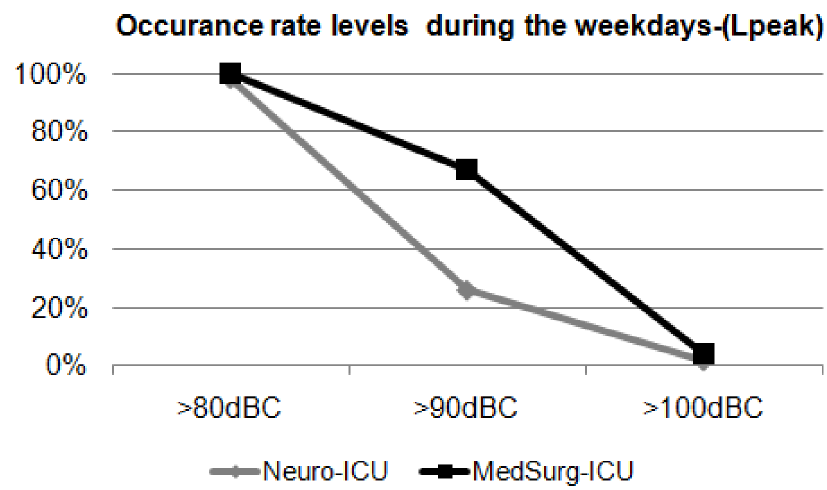


Figure 2.12 Occurrence rate of Lpeak noise levels during the weekdays in the two units

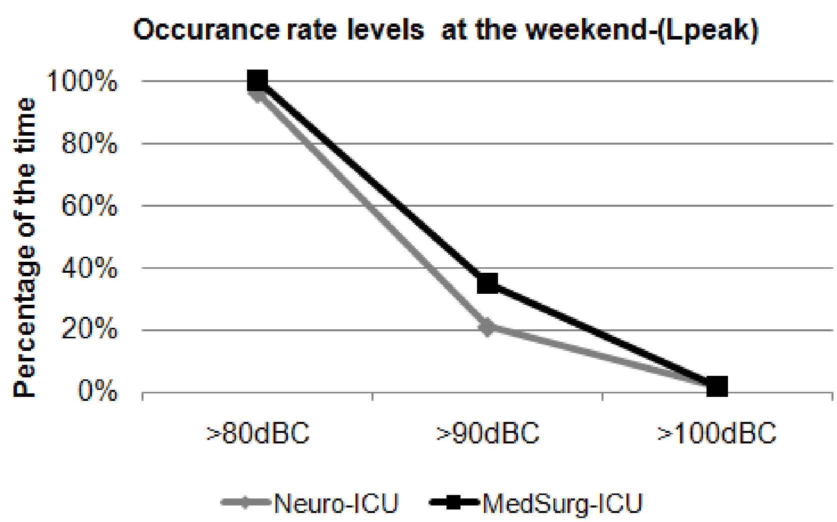


Figure 2.13 Occurrence rate of different Lpeak noise levels during at the weekend in the two units

Noise levels during the day times, night times and shift change

The second set of objective noise level measurements is conducted to assess noise level differences during different times of the day. The overall averaged Leq levels at the Neuro-ICU and MedSurg-ICU nurse stations range between 58-61dBA, 55-58dBA and 59-61dBA during the day, night and shift change time, respectively. Given these results, the difference between two wards in comparing different times of the day is either imperceptible or just perceptible to the human ear (Mehta et al. 1997).

However, the occurrence rate of mid-level transient sounds is higher in the MedSurg-ICU at all times of the day as shown in Figure 2.14, Figure 2.15 and Figure 2.16. The difference between the two units is much more evident during the day times and shift changes as compared to night times. In the MedSurg-ICU, more percentage of the time Lpeak noise levels exceed 90dBC during the day times and shift changes compared to night times. The occurrence rate of the mid-level transient sounds at the Neuro-ICU nurse station does not vary much during the different times of the day.

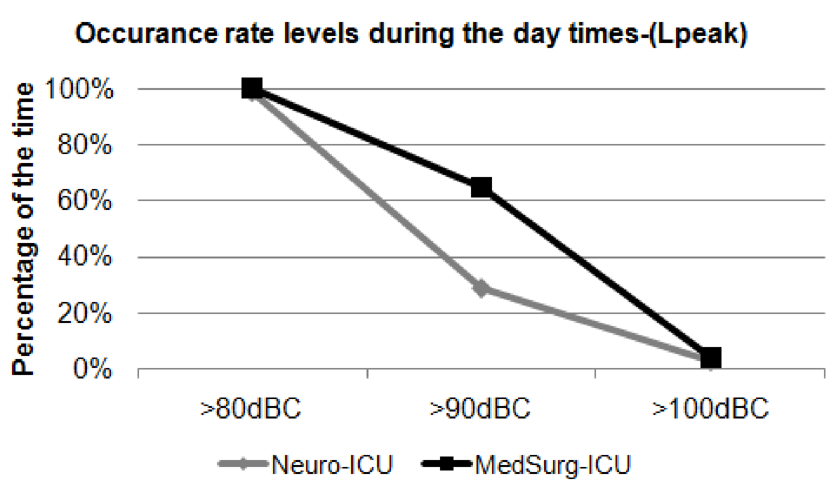


Figure 2.14 Occurrence rate of different Lpeak noise levels during the day times in the two units

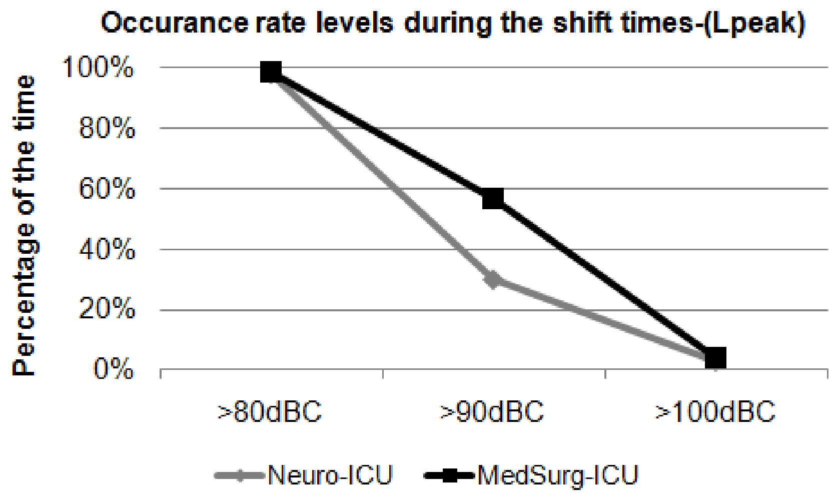


Figure 2.15 Occurrence rate of different Lpeak noise levels during the shift changes in the two units

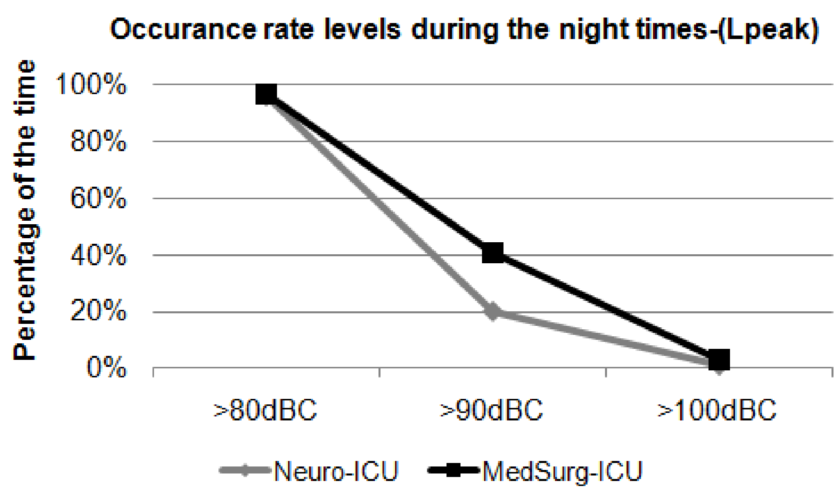


Figure 2.16 Occurrence rate of different Lpeak noise levels during the night times in the two units

Overall noise levels

For the third set objective noise level analyses, entire 96h data collected at the nurse station of each unit are considered. Sound samples collected from Thursday-Monday at each nurse station are averaged to calculate overall noise levels. Overall averaged noise levels at the nurse stations of two units range from 56-60 dBA Leq, 97-105 dB Lmax, 54-57dB Lmin, 113-120dBC Lpeak (Figure 2.17). As before, based on Leq the difference between two unit nurse station sound environments is just perceptible to human ear. The difference between two unit sound environments emerges for mid-level transient sounds. Figure 2.18 shows the overall levels at the two unit nurse stations where Lpeak exceed 90dBC more often in the MedSurg-ICU (53%) than in the Neuro-ICU (24%).

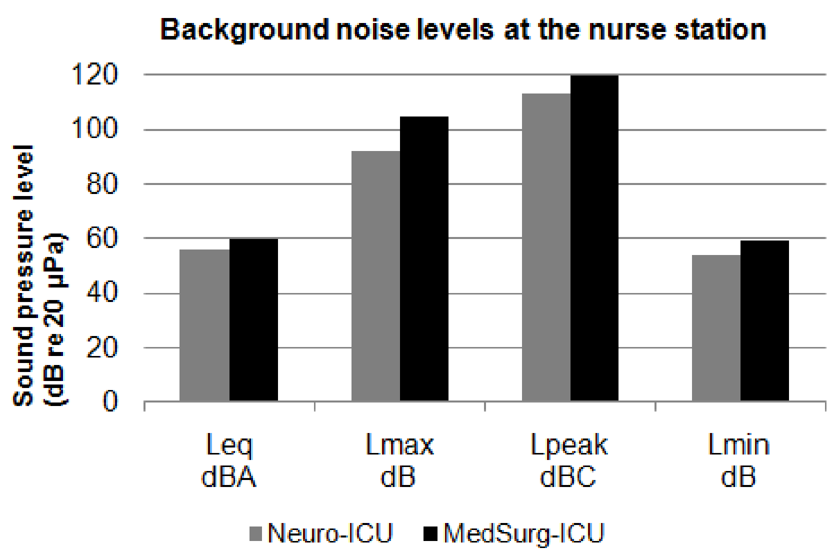


Figure 2.17 Overall Leq, Lmax, Lpeak and Lmin levels in the two ICU`s

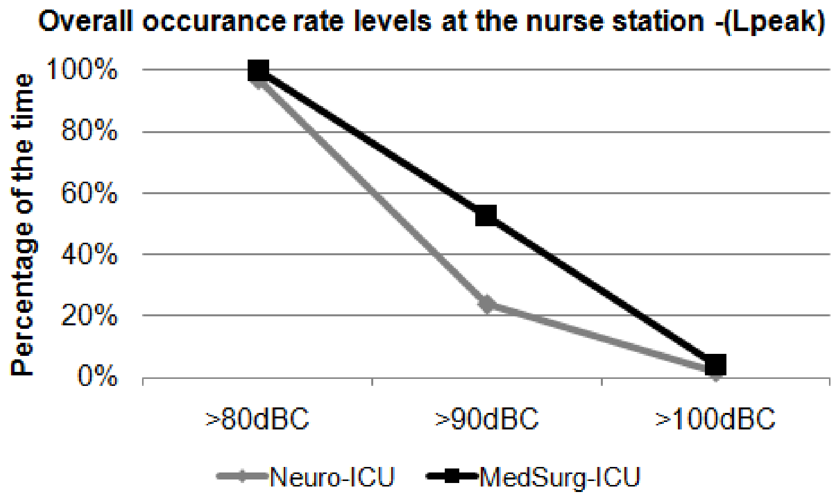


Figure 2.18 Overall occurrence rates of Lpeak noise levels in the two ICUs *(Please note that Figure 2.18 and Figure 2.4 are not the same. Figure 2.4 represents the occurrence rate of different LMax noise levels and Figure 2.18 represents the occurrence rate of different LPeak noise levels)*

2.3.4 Discussion

Empirical study 2 conducts objective and subjective noise level analyses to assess changing sound environment characteristics of each unit over time and assesses whether occurrence frequency of transient sounds track with the nurse loudness and annoyance perceptions during different times of the day and days of the week.

The first set of occurrence rate analysis indicates that MedSurg-ICU is consistently more impulsive at all times compared to Neuro-ICU. However, occurrence rate of mid-level transient sounds in the MedSurg-ICU is substantially higher compared to the occurrence rate of mid-level transient sounds in the Neuro-ICU only during the day time and shift change. These results are consistent with the perceptions of nurses in the two units. Nurses have found MedSurg-ICU more annoying and louder at all times. However significant differences between perceptions of the nurses in the two units have occurred only during the day time and shift change.

The second set of occurrence rate analysis indicates that MedSurg-ICU is consistently more impulsive compared to Neuro-ICU during the weekdays and the weekend. However, occurrence rate of mid-level transient sounds is substantially higher in the MedSurg-ICU compared to the occurrence rate of mid-level transient sounds in the Neuro-ICU only during the weekdays. These results are also consistent with the perceptions of nurses in the two units. Nurses have found MedSurg-ICU more annoying and louder during the weekdays and the weekend. However significant differences between perceptions of nurses in the two units only have occurred during the weekdays.

In the third set of occurrence rate analysis, the entire 96h data collected at the nurse station of each unit is considered. The results indicate that the occurrence rate of mid-level transient sounds is substantially higher at the nurse station in the MedSurg-ICU compared to the occurrence rate of mid-level transient sounds at the nurse station in the Neuro-ICU. This result is also consistent with the perceptions of the nurses in the two units. As presented in Table 2.2, MedSurg-ICU nurses have found the nurse station in their unit significantly more annoying and louder compared to the Neuro-ICU nurses.

Overall, occurrence rate analysis findings track with the loudness and annoyance perceptions of the nurses in the two units. This suggests the potential effectiveness of occurrence rate in predicting the nurse annoyance and loudness perceptions in ICUs.

2.4 EMPIRICAL STUDY 3

EFFECTS OF PARTICULAR HOSPITAL NOISE SOURCES

2.4.1 Scope

Clinical alarms are impulsive and frequently reoccurring sound events in ICUs. The previous empirical studies (1 and 2) discussed in the last two sections have highlighted potential negative impacts of impulsive characteristics of hospital sound environments on staff outcomes. As an extension of earlier empirical studies, a third empirical study is presented below that assesses the effects of a particular highly impulsive sound event (i.e., clinical alarms) by comparing the nurse outcomes in the two ICUs.

2.4.2 Methodology

Nurse perceptions

Subjective noise level analysis is conducted by using the data collected in empirical study 1. In addition to the components previously discussed, the survey also includes questions about alarm-induced nurse outcomes. For methodology details, please refer to section 2.2.2.

2.4.3 Findings

Effects of alarms and overall-noise in the two ICUs

A subjective noise level analysis is conducted to compare nurses` disturbance levels due to alarms in the two units. Mean perception ratings of the alarm-induced nurse outcomes in the MedSurg-ICU and Neuro-ICU are shown in Table 2.7. The effects of alarms on the MedSurg-ICU nurse outcomes are consistently significantly higher than the effects of alarms on the Neuro-ICU nurse outcomes. To restate, the MedSurg-ICU nurses have perceived alarms as louder, more annoying, and having higher negative impacts on their health, work performance, and anxiety levels. Moreover, the difference between the two units is the highest for anxiety compared to the other outcomes. In the MedSurg-ICU, the trend is that alarms have a greater impact on particular nurse outcomes of anxiety levels and loudness perceptions as compared to the other outcomes. In the Neuro-ICU, the trend is that alarms have the highest impact on nurses` loudness perceptions as compared to the other outcomes. All of the other outcomes in the Neuro-ICU are on average less than 3.0, which would correspond to "disagreement" ratings on the 5-point scale. This indicates that on average the Neuro-ICU nurses have not perceived alarms as contributing to outcomes with perhaps the exception of loudness.

Table 2.7 Perceived medical alarm-induced outcomes (i.e., loudness, annoyance, work performance, health and anxiety) of the nurses in the two ICUs. Higher numbers represent more negative perception.

	Alarm-induced loudness	Alarm-induced annoyance	Alarm-induced work perf.	Alarm-induced health	Alarm-induced anxiety
Neuro-ICU	3.2	2.6	1.8	1.8	2.3
MedSurg-ICU	4.0*	3.4**	2.8**	3.0**	4.0**

* The mean perception rating is significantly higher at 0.05 level ($p<0.05$)
** The mean perception rating is significantly higher at 0.01 level ($p<0.01$)

Table 2.8 Distribution of medical-alarm induced outcomes (i.e., loudness, annoyance, work performance, health and anxiety) of the nurses in the two ICUs

	5-point scale	Alarm-induced loudness	Alarm-induced annoyance	Alarm-induced work perf.	Alarm-induced health	Alarm-induced anxiety
Neuro-ICU	*Completely disagree-1*	6.0%	30.0%	3.0%	60.0%	42.9%
	Somewhat disagree-2	12.0%	21.1%	15.7%	17.1%	20.0%
	Neither agree nor disagree-3	13.0%	20.0%	20.7%	14.3%	8.6%
	Somewhat agree-4	34.3%	25.4%	10.0%	2.9%	22.8%
	Completely agree-5	23.0%	5.0%	8.6%	5.7%	5.7%
MedSurg-ICU	*Completely disagree-1*	0.0%	9.1%	5.0%	19.8%	8.8%
	Somewhat disagree-2	17.4%	18.2%	9.0%	18.4%	4.3%
	Neither agree nor disagree-3	8.7%	13.6%	12.4%	13.0%	13.0%
	Somewhat agree-4	30.4%	35.4%	28.4%	15.0%	30.4%
	Completely agree-5	43.5%	22.7%	22.0%	29.8%	43.5%

The nurses in the two units have been also asked to rate their level of agreement with the following statement: “I sometimes tune out the alarms.” The majority of the nurses “somewhat agree” with this statement (Figure 2.19). Only 20% of the nurses completely disagree with this statement.

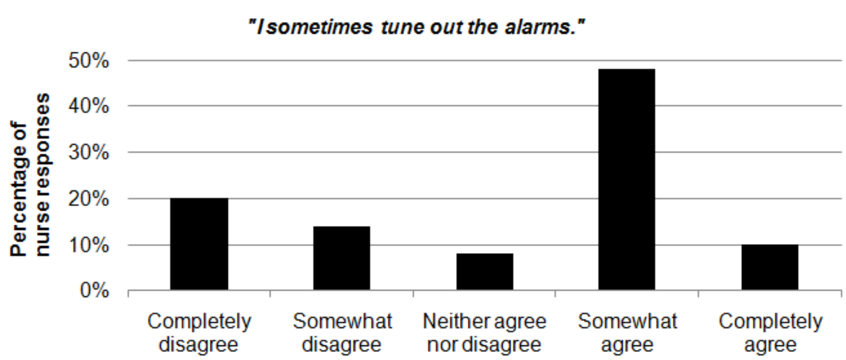


Figure 2.19 Percentage of nurses who agreed that they sometime tune out alarms averaged across the two units

2.4.4 Discussion

This study compares the effects of clinical alarms on nurse outcomes in the two ICUs. Alarms are one of the highly impulsive sound events that occur frequently in the ICUs. Regardless of their good intent, alarms can be highly disruptive of nurse outcomes. Furthermore, effects of clinical alarms on nurse outcomes can vary significantly between different care settings. For example, in the MedSurg-ICU nurses have found clinical alarms more disruptive of their outcomes (i.e., health and performance outcomes, anxiety, annoyance, and loudness perceptions) compared to nurses in the Neuro-ICU. This finding also agrees with occurrence rate analysis findings introduced in Section 2.2.3 and Section 2.3.3. According to two empirical study findings, the occurrence frequency of mid-level transient sounds is greater in the MedSurg-ICU compared to the occurrence frequency of mid-level transient sounds in the Neuro-ICU. Furthermore, alarms providing wrong information known as “false alarms” potentially lead to misconceptions and result in unwanted situations. Unfortunately, considerable amount of the Neuro-ICU and MedSurg-ICU nurses have reported that they sometimes tune out clinical alarms.

CHAPTER 3

CHARACTERISTICS OF PATIENT AUDITORY MONITORING

In complex hospital sound environments, caregivers conduct vital tasks including patient auditory monitoring. Chapter 2 examined the overall relationships between subjective perception and objective sound level measurements to gain a more thorough grasp of how perceptual and physical acoustic parameters interact in the ICU setting. Further, the Chapter 2 research suggested that the Acoustic qualities of hospital sound environments can have significant impact on nurses` auditory monitoring performance. Chapter 3 focuses specifically on the concept of auditory monitoring by providing a comprehensive overview of the factors related to auditory monitoring including previous research related to the topic; and presents the results from a case study comparing nurses` auditory monitoring performance in two ICUs with different architectural designs.

3.1 LITERATURE REVIEW

3.1.1 Patient monitoring in critical care units

3.1.1.1 Overview of patient monitoring

Today's ICUs are the outgrowth of respiratory care units established to provide continuous patient monitoring, and life support treatments for patients suffering from polio or tetanus in the early 20th century (Berenson, 1984). The establishment of these units was initiated by the invention of a mechanical ventilator called the "iron lung" in the late 1920s. In the 1960s, ICUs started providing electronic monitoring. Originally, electronic monitoring was developed for cardiac rhythm monitoring to preserve the health of relatively stable patients (Russell, 1979).

In today`s ICUs, continuous monitoring is provided for critically ill patients by a wide range of technological services, continuous observation, and frequent measurement of vital signs (Safar, & Grenvik, 1971). Critical care units differ based on their specialty (e.g., multispecialty, specialty); however, patient monitoring is key for all types. In multispecialty ICUs (e.g., Medical Surgical-ICU), seriously ill medical surgical patients with a wide spectrum of illnesses are provided care. In specialty ICUs, patients with similar problems or specific diseases are provided care such as care of premature or critically ill newborn (Neonatal-ICU), care of critically ill and injured children (Pediatric-ICU), adult cardiac disease (Cardiac-ICU), trauma care, care of multiple organ dysfunction in the surgical ICU (Surgical-ICU), care of neurological and neurosurgical patients (Neuro-ICU).

Patients in ICUs generally suffer from different health problems including failing bodily functions, multiple and complex sets of medical problems requiring support for two or more organ systems (Bennett, & Bion, 1999). Patients are accepted to ICUs mainly because they need monitoring for potential disturbances to those who are critically ill, and receive life-supporting treatment or continuous intensive nursing and physician care (Berenson, 1984). ICUs typically differ based on the level of care provided such as Level-I, Level-II and Step-down critical care units (Miller, & Swensson, 2002). Typically Level-I critical care units house patients with multisystem failure, and complicated medical needs requiring continuous availability of sophisticated equipment and specialized medical staff. Level-II critical care settings typically offer care to patients with single organ failure. Step-down units or intermediate care patients typically require close monitoring but not intensive medication or therapy.

There is a growing demand for critical care in the U.S. There are approximately 6,000 ICUs caring for 55,000 critically ill patients each day (SCCM, 2006). About 16% of the annual admissions to U.S. hospitals are admitted to ICUs, which corresponds to about six million patients and 2% of the U.S. population (Kersten et al., 2003). ICU patients` health status requires more attentive monitoring as compared to standard nursing-floor patients. ICU diseases can develop rapidly in seconds as multiple underlying medical problems can interact and produce severe unpredictable physiologic complications (Hillman, & Bishop, 2004). Berenson (1984) indicated that 20% to 40% of the ICU patients died in the hospital after being transferred from the ICU to the regular medical floor. Providing an environment that is supportive of patient monitoring is necessary for patient safety, particularly in ICUs.

3.1.1.2 The profile of caregivers conducting patient monitoring

Critical care nurses provide care to patients who are very sick and critical care nursing can be a very demanding job. Critical care nurses are educated to provide highly technical expert care and trained to deal with end-of-life cases (Gross, 2006). They continuously provide vigilant efforts to maintain patient safety while working under time pressure.

Unfortunately, their workplaces are not always equipped with support work environments. Demanding work conditions and poorly designed work environments can lead to high levels of cognitive, physical, and emotional workload, negative health outcomes, and job dissatisfaction among ICU nurses (Aiken et al., 2002; Carayon et al., 1999; Ulrich et al., 2009). Findings indicate that emotional stress and working under time pressure can also lead to increased risk for work-related musculoskeletal disorders, physiological changes, increase in nurse sensitivity to pain, and perceived physical workload (Carayon et al., 1999). Moreover, according to American Association of Critical-Care Nurses (AACN) national survey, a significant portion of the nurses are not satisfied with their jobs: more than 16% of the nurses indicated that their intention is to quit their job in the following 12 months and about 27% in the next 3 years (Ulrich et al., 2009). Similarly, Aiken (2002) found that 1 in 4 bedside nurses is considering leaving their jobs in a year and half of the nurses reported high burnout range. Given these statistics, a significant drop in the number of nurses is feasible. A federal agency estimated that the shortfall of nurses could approach 800,000 by 2020 (DHHS, 2002).

On the other hand, there is some evidence showing positive impacts of improved environmental conditions such as hospital sound environments on nurse outcomes. The empirical studies in Chapter 2 compared the sound environments of two different ICUs and found significant differences between nurse outcomes in the different units due to the acoustic qualities of these sound environments. Another non-hospital study found that task supportive environmental conditions such as effective sound environments in the workplaces might help to buffer the effects of job stressors (Leather et al., 2003).

3.1.1.3 Patient monitoring and other critical nurse tasks

ICU nurses conduct different critical and non-critical tasks. Highly critical nurse tasks mainly relate to the care of the sick and maintenance of patient safety (Diers, 2004). Some of the tasks related with the care of the sick include skin wound care, managing pain, providing comfort, teaching patients and families how to manage their care after hospital discharge, adequate nourishment of patients, infection control intervention, and prevention of hazards. Nurse tasks that critically relate to patient safety include providing continuous patient monitoring for early detection of adverse events and complications, medication errors, and mobilization of resources for timely interventions and rescue (Aiken, 2005). Nurse time is also allocated with non-critical tasks such as waiting on other systems (e.g., delivery of medication, lab results), retrieving patient supplies, and looking for equipment (Hendrich et al., 2008). However, the same study found that majority of the nurse time (78%) is spent on clinical nursing practice functions including patient monitoring and patient care activities.

3.1.1.4 Types of patient monitoring

Critical care nurses conduct highly routine patient monitoring tasks. These tasks require vigilant attendance to multitude of cues and continuously alert minds, vigorous body states, and prompt-accurate decisions (Carnevale, 2009). ICU nurses continuously monitor the patients` health status and maintain their normal bodily conditions by assessing visual and auditory cues. To recognize any irregularities, nurses remain attentive to the patients' physiologic status and treatment devices, and they are continually "tuned in" to the immediate recognition of any disruption in the patients` condition. They must remain tuned in even when performing routine maintenance activities (e.g., medication preparation, blood procurement). In the event of any abnormal changes, nurses instantly evaluate the significance of the event to patient safety, and initiate an appropriate response and effective intervention if required.

3.1.1.5 Visual Patient Monitoring

Since the late 19^{th} century, visual patient monitoring has been a significant element of nursing practice. Visual cues have been used for the early detection of some health complications. Examples include changes in the color or texture of the skin (e.g., rashes, bruising), asymmetric chest movements, abnormal bleeding, proper placement of the patient on the bed, invasive equipment around the patient bed, and any other condition that might be related with distress and patient comfort (Downes, 2009). Effective visual monitoring can be enabled by the absence of any barrier between observer and target. It is identified as inadequate when nurses are assigned to patients whose rooms are physically distant from each other (Kalish, 2005). To maximize the patient visibility, the design of today's critical care units aim to provide a direct line of vision between every patient room and nurse work areas by adopting different design strategies such as radial design layout and distributed nurse stations (SCCM, 1995).

3.1.1.6 Auditory Patient Monitoring

Like visual monitoring, assessment of auditory cues has become a significant component of nursing practice (Downes, 2009). As a part of the auditory monitoring process, nurses attentively listen to the auditory cues, detect the ones that might present risks to patient safety, and localize them to provide proper and immediate response to abnormal sounds. ICU nurses develop auditory skills that enable them to differentiate auditory cues from each other and immediately recognize the meaning of each while considering the potential risks to the patient health status over time.

Auditory cues can be generically classified as alarm or non-alarm. An immediate response to triggered alarms in ICUs includes physically assessing the patient and resolving the situation (Richardson, 2004). Nurses` response to an "urgent" medical alarm in a timely manner can be highly critical. During personal interviews with ICU nurses, appropriate initial response time to a highly urgent alarm was found to be 30 seconds or less. Caregiver response time to a moderate risk alarm is expected to be 1-3 minutes, and to a low risk alarm 3-5minutes for patient safety (Phillips, &Barnsteiner, 2005). Lack of proper monitoring can delay the response time and even disable the early detection of complications which can result in serious patient injury and death due to ventilator failure, breathing circuit disconnections, etc. (ECRI, 1986). According to ECRI, ventilator dependent patients need special attention and they should never be left unattended. Otherwise, caregivers should limit their visits in the unit to only locations where they can hear and rapidly respond to alarms. This is mainly because ventilator dependent patients cannot breathe spontaneously for substantial periods of time and cannot mutually ventilate themselves. Impaired gas exchange (i.e., supply of adequate oxygen to the body and elimination of carbon dioxide) can lead to poor tissue perfusion which leads to a reduction in oxygen delivery to cells as well as a retention of CO2 in the blood stream (Hinchliff, Montague, &Watson, 1988).

Nurse effectiveness in providing immediate response is significantly related with caregivers vigilance level (Clarke, &Aiken, 2003). Growing evidence from hospital and non-hospital research also indicate the effect of environmental factors on nurse work performance utilizing auditory cues. These qualities are discussed details in the following sections.

3.1.2 ICU auditory cues

With the adoption of computer based patient monitoring systems, nurses started monitoring the clinical alarms as well as non-alarm sounds. Today, electronic monitors are extensively used in critical care units and medical alarms are accepted as one of the primary auditory cues key for patient safety.

A variety of different medical equipment is used in ICUs. Each type of equipment can produce multiple alarms to communicate about the urgency level of the alarming condition such as high-level urgency (emergency alarms), medium-level urgency (cautionary alarms) and low-level urgency (alerting alarms) (CEN, 1995; Chambrin et al., 1999; Meredith, & Edworthy, 1995). High-level urgency alarms (e.g., 3-star cardiac alarms) indicate an urgent situation that can lead immediately to a vital problem and requires immediate attention of the registered nurses. Medium-level urgency alarms (e.g., 2-star cardiac alarms) indicate a dangerous situation and require rapid attention of the registered nurses. Low-level urgency alarms (e.g., equipment failure that would pose a minimum adverse effect) indicate an alert situation that still requires the attention of staff but does not necessarily require registered nurse response.

Most ICU patients are attached to some combination of medical equipment which can be grouped in three categories: patient monitors, infusion devices, and life-support equipment (Hirose et al., 2005). Some examples of patient monitoring systems include electrocardiogram-blood pressure monitors, noninvasive blood pressure monitors, pulse oximeters, and capnometers (Kerr, &Hayes, 1983). Some of the infusion devices include IV pumps and feeding pumps. Respiratory ventilators, intra-aortic balloon pumps, hemodialysis units, and anesthesia machines are some of the commonly used life support equipment in ICUs. Some of the most commonly used medical equipment in ICUs is cardiovascular monitors, respiratory ventilators, infusion devices, and dialysis machines. Given the plethora of medical devices, a high density of critical medical alarms is not uncommon in modern ICUs. One study reported that there are at least 33 different medical alarms that nurses continuously monitor in ICUs (Cropp et al., 1994). The same study also found that during an average hour on the day shift at least 50 audible medical signals occurred in a critical care unit.

In addition to clinical alarm sounds, effective monitoring of non-alarm sounds can be very important for the early detection of health complications. These sounds can be categorized under non-speech and speech sounds. Examples of non-speech sounds include patient bodily sounds such as gagging (the sound similar to choaking), strider (constriction in breathing pattern), and sleep apnea (irregular breathing patterns). Safety threatening sounds might include patient falls, the sounds of leaking air from the oxygen tube, and sounds of falling objects. ICU nurses typically monitor breathing rates, respiratory efforts, pattern of respiration (i.e., rhythm and depth), presence of audible wheeze, and dry cough to assess patient respiratory health (Owen, 1982). Examples of critical speech sounds include help calls by patients and caregivers, announcements from overhead pagers, medical conversations either conducted on the phone (e.g., between nurse and pharmacists) or in person (e.g., between physician and nurse).

3.1.3 Factors impacting auditory monitoring

Monitoring of both alarm and non-alarm auditory cues can be significantly affected by environmental factors. One study indicated that improved hospital sound environments can have a significant impact on speech intelligibly outcomes (Blomkvist et al., 2005). In addition to environmental factors, strategic design of auditory cues such as alarms and drug names can also reduce the risks to patient safety. Similarities in orthographic (i.e., spelling) and phonological (i.e., sound) qualities of drug names increase the probability of making false recognitions (Lambert et al., 2001). According to national statistics, 1 out of 4 medical errors in the U.S. involves drug name confusion (U.S. Pharmacopeia, 1997). Furthermore, according to another study the development of new auditory warnings based on vowel sounds can be less irritating and less susceptible to masking by the background noise (Stanford, Mclntyre, & Hogan, 1985).

There are also studies focusing on three of the individual components of the auditory monitoring process: sound detection, sound recognition, and sound localization. The findings of hospital and non-hospital research on these three components are discussed in the following sections. Overall, sound detection, recognition, and localization can be very challenging tasks in noisy, multi-source, or reverberant environments. Studies conducted in controlled lab environments as described below provide some insight to the attributes that might have impact on nurse auditory monitoring.

3.1.3.1. Sound detection

Sound detection involves the ability to hear an auditory cue, or "target." In settings like ICUs, detection of auditory cues in noisy and multi-source environments is inevitable. The human auditory system is capable of focusing attention on one source/speaker, even when there are multiple competing sound sources in the background (Cherry, 1953). This phenomenon is known as the "cocktail party effect". However, Stifelman (1994) indicated that listening to the target speech signal while simultaneously exposed to two other competing background signals may require too much effort. There is some evidence indicating that such demanding sound tasks can be supported by specific acoustic qualities of sound targets and competing signals. For example, Treisman (1964) found that listeners` primary signal monitoring performance improved when competing background signals had similar acoustic features to each other. This phenomenon is referred to as "auditory stream segregation" (Bregman, 1990). According to this theory, two competing sound signals with similar acoustic features (e.g., pitch, spatial location) form one single auditory stream. This enables the perception of multiple competing signals as one single interfering signal. Bess and Humes (1990) found that human hearing is most accurate for frequencies between 1kHz-4kHz, the frequency range also corresponding to primary intelligibility of speech signals**.** Competing signals that are in the same frequency range as speech signals (1kHz-4kHz) thus can potentially mask a speech target. Other research indicated that a frequency difference of 110Hz between target and competing signals can improve the intelligibility of the target speech signal (Brokx, & Nooteboom, 1982). Blauert (1997) indicates that intelligibility of target sounds with and without meaning might have a significant impact on signal detection.

There is also some evidence showing that at certain sound pressure levels speech detection can be more effective. According to Kobayaski (2007), the minimum listening difficulty occurred when the target speech level was 50-55dBA. At higher or lower speech levels, listening difficulty increased. The same study indicated that humans have a tendency to increase their voices as loudness increases, a well-documented phenomenon known as the "Lombard Effect." Speech levels generally stayed constant when the background level was less than 40dBA. However, when background level was higher than 40dBA, the talker adjusted his/her speech level to maintain approximately 15dBA of signal-to-noise ratio.

3.1.3.2 Sound recognition

Sound recognition involves identifying or interpreting an auditory cue. One study conducted listening tests with nurses to assess their ability to identify critical alarms occurring in ICUs (Cropp et al., 1994). It was found that only 50% of critical alarms presented to nurses were identified correctly. Moreover, caregivers with more than one year experience scored higher than those with less than one year. Wallace et al. (1994) also highlighted difficulties experienced by caregivers in detecting alarms in operating rooms. These findings might be associated with limited capabilities of human auditory system. Patterson and Mikoy (1980) suggested that humans are not able to easily learn and remember the significance of more than 8 different sounds even in unstressed conditions. Similarly, another group suggested that 6-10 auditory warning signals would be the optimum (Momtahan, &Tansley, 1989). Lambert et al. (2001) highlighted recognition difficulties associated with complex and diverse of acoustic qualities of auditory cues. According to the study findings, orthographic (i.e., spelling), and phonological (i.e., sound) similarities potentially increase the probability of caregivers` making recognition memory errors.

Recognizing a specific medical alarm is difficult in part due to the similar acoustic content of the many different alarms in an ICU. Some studies have documented the acoustic qualities of medical alarms. Wallace (1994) measured the intensity and frequency of 26 anesthesia equipment alarms in an unused operating room suite. The majority of the alarms consisted of mid to high range frequencies ranged between 250Hz to 8000Hz. Almost all of the alarms were multi-frequency signals. Different from sine tones (a.k.a. pure tones), a multi-frequency tone consists of multiple frequencies. Nine of the alarms consisted of 4-5 different frequencies including 500, 1000, 2000, 4000, and/or 8000Hz. Other two alarms also had 250Hz content. Five of the multi-frequency alarms were limited to frequencies higher than 1000Hz and seven of them were limited to frequencies higher than 2000Hz. Only three of the twenty-six alarms were pure tones and had a frequency of 4000Hz. Loudness levels of these alarms ranged between 45dBA to 80dBA. A Japanese study documented the acoustic characteristics of 73 pieces of medical equipment (Hirose et al., 2005). Different from the findings of the previous study, the study found that 90% of the alarms generated by the equipment included only a single frequency and the majority had discontinuous patterns. The spectral content of the medical alarms activated by “biological information monitors” including ECG/BP monitor alarms, NIBP and pulse oximeter ranged between 500 and 4000Hz. The frequency level of the life support equipment including infusion pumps and ventilators ranged between 1000-4000Hz. Most of the time, the maximum (Lmax) and minimum (Lmin) sound pressure levels generated by the alarms exceeded 70dB and 50dB, respectively. The repeating module of the warning signal composed of alarm and silence known as “alarm cycle” was mostly 1s for different alarms.

To summarize, in U.S. hospitals medical alarms are expected to have multiple frequencies so that they are less likely to be masked by the background noise. For example, ASTM Standard F29.03.04 for anesthesia and respiratory care medical equipment alarm signals requires that medical alarms should have a fundamental frequency of 150-1000Hz and at least four frequency components between 300-4000Hz.

3.1.3.3 Sound Localization

Sound localization relates to auditory system’s ability to make decisions about the direction and distance of the sound event (Moore, 1997). Auditory information that is critical for sound localization is known as a “spatial” auditory cue. Various studies have been conducted in controlled lab environments to explore the attributes necessary for the assessment of spatial auditory cues.

Estimating distance and direction

Developments in binaural hearing research explain how the human auditory system uses binaural cues obtained by two ears during sound localization. The auditory system essentially assesses time and sound level differences between the sound waves arriving at the left and the right ear (Blauert, 2005). Due to the different path lengths to the two ears, the arrival times of the sound waves emitted from a single sound source are not always the same at the left and the right ear (Thompson, 1877). This acoustic principle is known as “inter-aural time difference” (ITD). On the other hand, existence of the head between the two ears creates an acoustic shadow and causes sound attenuation which leads to an “inter-aural (sound) level difference” (ILD) between the left and the right ears (Steinhauser, 1877). Follow-up studies found a frequency dependence of these two binaural cues (Rayleigh, 1907). According to Rayleigh’s “duplex theory”, ITDs are most critical for the localization of low-frequency sounds and ILDs are most critical for high frequencies.

The sound level of sources, a listener`s familiarity with sound events, and the acoustic quality of sources are the major factors for distance and direction judgments. For example, in a sound field free of reflecting surfaces, every doubling in distance produces 6dB reduction in the sound level at the ears. Distances longer than 15m (49ft) lead to an additional sound attenuation and slight change in the spectral balance of the sound reaching the ears (Ingard, 1953; Plack, 2005). This is mainly because air absorbs more high frequency energy than low frequency in relation to the length of the air path.

Study findings indicate that a listener's ability to make accurate directional estimations is associated with their familiarity with signals. Makous and Middlebrooks (1990) indicated a significant improvement in listeners` directional judgment skills after training. Most of them made errors of less than 5 degrees both in horizontal and vertical directions. Plenge and Bruschen (1971) found that subjects` directional judgment performance improved when short speech signals were pronounced by people that they are familiar with. The authors also reported listeners` tendency to report the unfamiliar signals as if they were coming from behind.

The acoustic quality of signals, such as duration and spectral content, also influence localization estimations. For example, Aschoff (1963) explored the effects of duration on direction estimations of the auditory system (cross ref. Blauert 1997). According to study findings, listeners were able to hear the noise circling around their heads when signals from circular array of loudspeakers were played with a slow switching speed. When switching speed was increased, the noise was heard to move between left and right sides. When the switching speed further increased, the auditory event was heard approximately in the middle of the head. As another example, Blauert (1997) explored the effect of spectral content on sound localization and conducted an experiment with 140 subjects by using pulses of white and pink noise. Approximately 90% of the subjects succeeded in their direction judgments. Sandel et al. (1955) found that the localization performance was worst around 1.5 kHz-3 kHz. According to another study, localization precision was best for frequencies between 200Hz-1 kHz and the error magnitude peaked around 3 kHz (Mills 1958) .

Effects of acoustic environment on sound localization

Listeners` ability to localize sounds varies depending on the acoustic environment. For example, in reverberant sound environments, sound localization can be very difficult. This is mainly because later-arriving reflections can reduce the impact of direct sound and early-arriving reflections necessary for sound localization. The human ear is capable of integrating early reflections (typically up to 50-80ms after the arrival of the primary signal) with the direct sound signal. However, strong and later-arriving reflections (typically those greater than 80ms after the arrival of the primary signal) can cause changes in the perception of the auditory event such as changes in the direction of the primary sound signal (Blauert, 1997). Hartman (1983) conducted listening tests in a controlled room with human subjects to assess the impact of signal qualities and room acoustics on sound localization performance. Subjects localized broadband sounds easier when design interventions were adopted to reduce reverberation time such as including absorptive surface and lowering ceilings. Compared to a higher ceiling condition, at a low ceiling configuration the reverberation time was about half of the high ceiling condition. The study also concluded that the localization of the sine tones is independent of the room reverberation time. In other words, when localizing sine tones the human auditory system is limited to benefit from the useful reflections in the *rooms*. Different from complex nature of the sounds in hospitals, sine tones are composed of a single frequency. As with sound detection, studies also show that sound level differences between target signal and competing signals can affect sound localization. Houtgast and Plomp (1968) suggested sound localization can be more effective if the level of competing noise is 15dB or more below than the target signal. Lorenzi et al. (1999) indicated sound localization accuracy remains unaffected by competing noise until a 0–6 dB signal-to-noise ratio is reached.

3.2 EMPIRICAL STUDY

CHARACTERIZING AUDITORY PATIENT MONITORING

3.2.1 Scope

Intensive Care Unit (ICU) patients are one of the most sensitive patient populations in a hospital. Mortality rates among ICU patients range between 10% to 20% in most hospitals (SCCM 2006). To promote patient safety, ICU nurses continuously monitor the health status of their patients, and strive to maintain appropriate bodily conditions by assessing visual and auditory cues, and responding immediately to abnormal changes. The ability to conduct uninterrupted patient monitoring is a challenging task for ICU nurses, in particular because of other competing tasks and environmental factors. Effective monitoring of visual cues is feasible in close proximity to the patient as it requires the absence of a barrier between observer and target. Study findings indicate that increased visibility of patients in the ICUs through design strategies can help improve patient safety (Joseph, & Rashid, 2007).

Different from visual monitoring, auditory monitoring is an “eyes-free” cue assessment technique. When caregivers` hands and eyes are busy, auditory monitoring can enable uninterrupted monitoring of patients from different locations in the care settings. Therefore, it is one of the early requirements for novice nurses to familiarize themselves to auditory cues that might pose a risk to patient safety. Nurses` ability to conduct auditory monitoring more effectively can be enhanced by improving the qualities of hospital sound environments. Even though the significance of visual monitoring in ICUs for patient outcomes including patient falls has been well documented, there is limited information about auditory monitoring. This study aims to provide (1) a comprehensive overview of previous research related to auditory monitoring; and (2) to describe a case study examining auditory monitoring in two ICUs.

3.2.2 Methodology

A case study is conducted in the two ICUs described in Chapter 2 in order to assess the perceived auditory monitoring abilities of nurses. In addition to the components already discussed, the online survey contains questions about nurse tasks highly important for patient monitoring, ICU sounds necessary for patient safety, and key listening locations in the unit. Please refer to section 2.2.2 for additional details on the subjects.

The units are similar in staffing and patient acuity as discussed in section 2.2.2: similar number of private patient rooms and staffing models (intensivists and nurse practitioners), acuity levels of patients, nurse working hours. On the other hand, the designs of these two units are different with the following specific differences that might impact auditory monitoring. As shown in Figure 3.1, different from the design principles of Neuro-ICU, MedSurg-ICU layout is designed to be more compact to reduce walking distances that results in smaller volumes and shorter corridors. For example, total length of the staff corridors in MedSurg-ICU is 73 m (240 ft) while it is 183 m (600 ft) in Neuro-ICU. Moreover, spaces in the Neuro-ICU are installed with high performance acoustic ceiling tiles (with higher sound absorption qualities), while it is only regular ceiling tiles (with less sound absorption qualities) from 1980`s in the MedSurg-ICU.

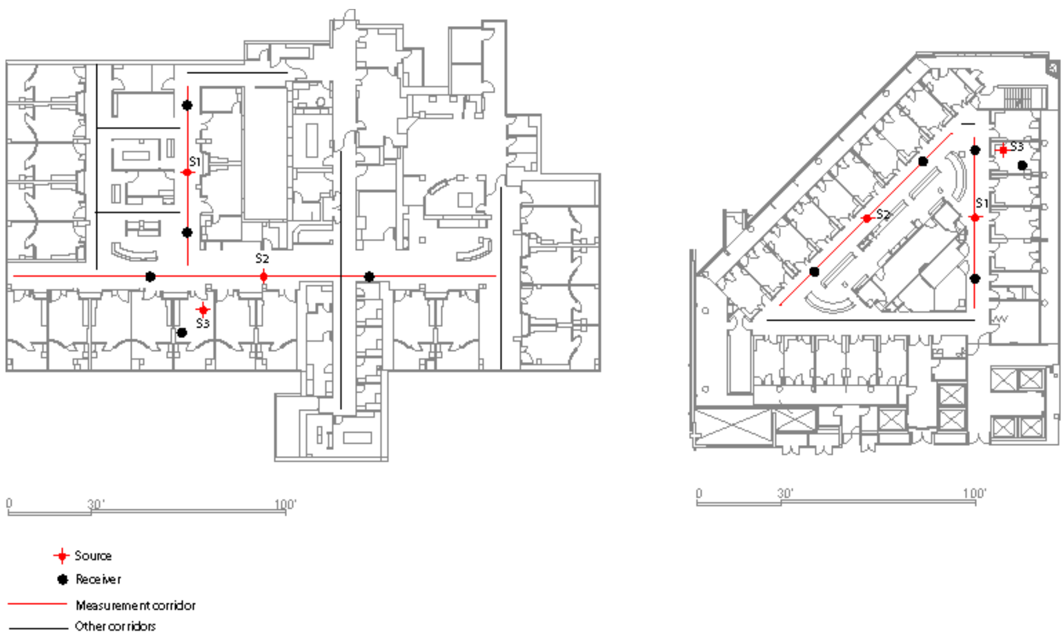


Figure 3.1 Floor-plans of two ICUs showing circulation patterns and impulse response measurement locations

As discussed earlier, reverberation can potentially impact auditory monitoring. Therefore, impulse response measurements are conducted to objectively assess the reverberant qualities of the corridors in the two wards. The impulse response measurements have taken place at 6 different receiver locations in two hallways and in an unoccupied patient room in each ward as shown in Figure 3.1. The measurement system consists of a GSR omni-directional dodechahedral loudspeaker with Outline amplifier, ProSonus EASERA Gateway data acquisition system (DAQ), laptop equipped with EASERA software v.1.1, and Larson Davis 824 sound level meter microphones. A maximum length sequence (MLS) excitation signal is used. The sound source is located slightly off the center of the *rooms* in each unit. The receivers are located about 7.6m-10.6m (25ft-35ft) away from the source in each hallway. In the unoccupied patient rooms of the two wards, the source is also located about 1.3m (4.5ft) away from the receivers. In both the corridors and patient rooms of the two wards, receivers are placed at distances outside the critical distance to avoid significant impact of direct sound on the reverberation time. In the patient rooms of the two wards, the critical distances range between 0.76m- 0.9m (2.5ft-3ft). In the corridors the critical distances are 4.5m (15ft) in the Neuro-ICU and 1.8m (6ft) in the MedSurg-ICU.

3.2.3 Findings

Perceived importance of nurse tasks

The Neuro-ICU and MedSurg-ICU nurses have been asked to rate the perceived importance of different methods of patient monitoring according to their relevance in critical care nursing. The distribution of the nurse responses with the distribution normal curve are shown in Figure 3.2. More than 85% of the Neuro-ICU and MedSurg-ICU nurses “completely agreed” that visual and auditory patient monitoring are important tasks in critical care nursing, while the majority of the rest “somewhat” agreed that these two tasks were important. Mean levels for perceived importance of visual and auditory monitoring are 4.7 and 4.8 out of 5, respectively. Based on significance test results, there are no statistically significant differences between the perceptions of nurses in the two units ($p>0.05$).

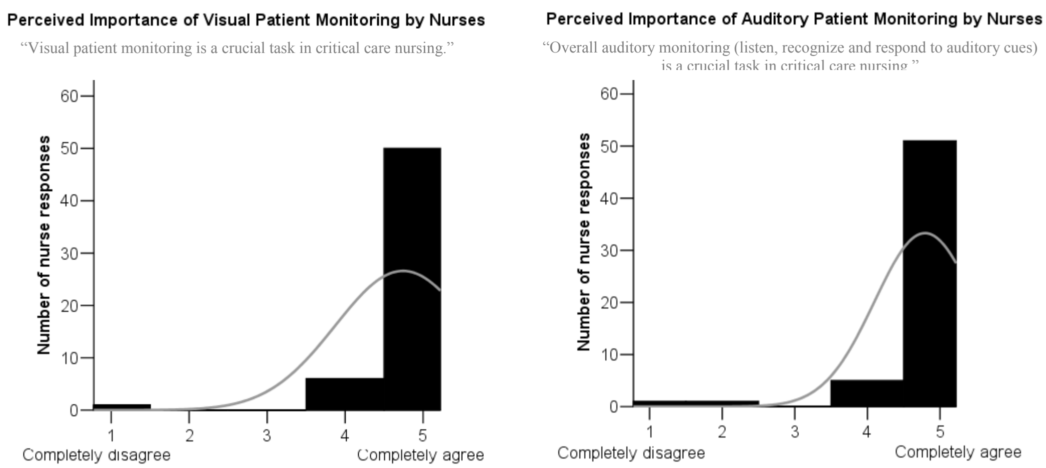


Figure 3.2 Perceived importance of visual vs. auditory monitoring averaged across the two units

More detailed analyses are shown in Figure 3.3 which represents the perceived importance of auditory monitoring components in relation to visual monitoring. The majority of the nurses from two units believe that individual sound tasks conducted during auditory monitoring (i.e., ability to hear, differentiate and localize auditory cues) are also highly important nurse tasks. Based on analysis of variance test results, there are no significant differences between the perceived importance of visual monitoring and three auditory monitoring tasks ($p>0.05$).

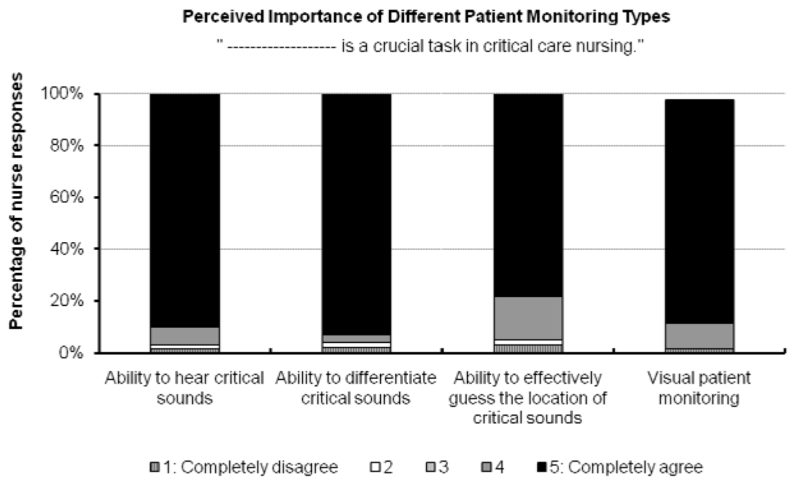


Figure 3.3 Perceived importance of three auditory monitoring tasks vs. visual monitoring averaged across the two units

Perceived importance of auditory cues

Nurses from both units have been also asked to rate the importance of different medical alarms for patient safety. Results are shown in Figure 3.4. Almost all nurses believe that ventilator alarms are "very" critical for patient safety. More than 70% of the nurses reported hissing sounds of the respiratory ventilators are also very critical for patient safety. These two auditory cues are monitored to ensure patient's adequate and proper breathing. The hissing sound of the ventilator equipment is an indicator of proper functioning of pressure relief valves. The alarms generated by the medical ventilator might be associated with different events such as secretion in endotracheal tube (ETT), a kink in the vent tubing, patient biting on ETT, increased airway pressure, a disconnect in the vent tubing, displaced ETT, patient anxiety or pain, hypoxia, hypercapnia, and lack of full delivery of breath.

As shown in Figure 3.4, the perceived importance of other non-ventilator alarms (patient monitor, IV-pump, nurse call and feeding-pump alarms) varied. About 85% of the nurses believed that patient monitor alarms are “very” critical for patient safety. Patient monitor alarms inform any abnormal changes in the physiologic parameters such as heart rate, temperature, ECG, SpO_2, blood pressure, and CO_2. A specific type of patient monitor alarm, known as the “code” indicates highly critical occurrences that might have life-and-death implications such as heart failure, cardiac arrest. The percentage of nurses who believe that the IV-pump alarms and nurse call alarms are “very” critical for patient safety was 63% and 55%, respectively. The majority of the rest believe that these tasks are “somewhat” critical. Not many nurses (20%) have rated the feeding pump alarms as “very” critical for patient safety, but about 60% of the nurses have reported that they are “somewhat” critical for patient safety.

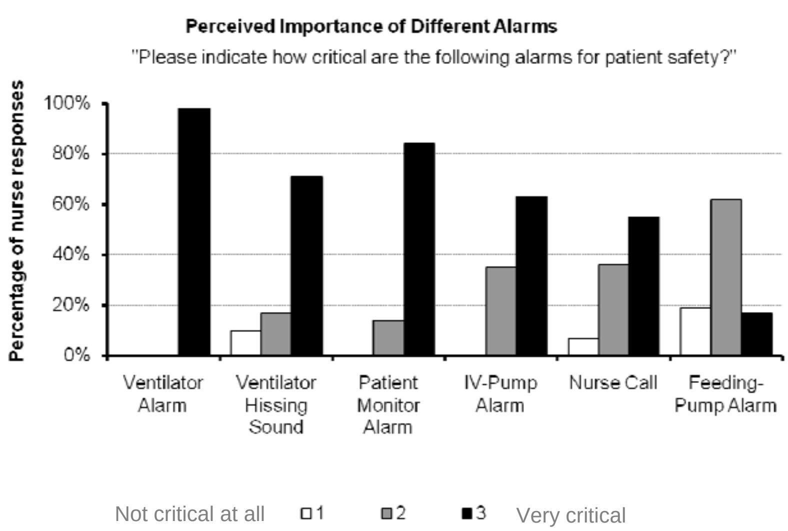
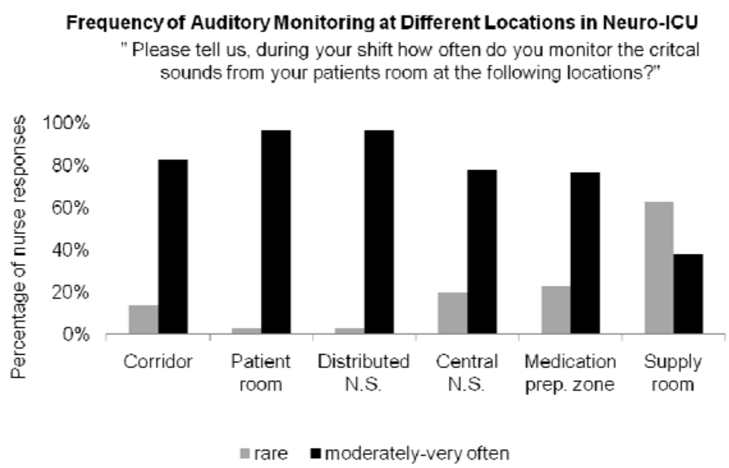


Figure 3.4 Perceived importance of different medical alarms for patient safety averaged across the two units

In addition, nurses have been also asked to report any other auditory cues including alarm and non-alarm sounds necessary for patient safety. Some of those reported alarms include bed rail alarms, bed exit alarm, CRRT alarms (from the dialysis machine), PCA-pump alarms (from the medication-dispensing unit), V-tach, V-fib, and physiological parameters (from patient monitors). The latter three as well as the code alarms might lead to rapid heart failure. Examples of non-alarm auditory cues mentioned include staff help calls which might indicate the need for additional resources and assistance or a significant problem with the patient, patient help calls which generally occur when a patient is not capable of reaching the call light, unusual or distress noise from patient rooms (e.g. patient getting out of the bed, patient fall), family help calls, and patient bodily sounds.

Key listening locations in the MedSurg-ICU and Neuro-ICU

Nurses have been also asked how often they use auditory monitoring in various locations in their ICUs. Specifically, they have been asked about corridors, patient rooms, central nurse stations, medication prep zones, and supply rooms. Note that both ICUs contained these various spaces. Additionally, nurses in the Neuro-ICU have been asked about distributed nurse stations, as this is a design feature unique to this unit and distributed nurse stations are not contained in the MedSurg-ICU. As Figure 3.5 shows, in both the Neuro-ICU and MedSurg-ICU, the locations where the most auditory monitoring occurred are the corridors, patient rooms, and central nurse stations. The Neuro-ICU nurses additionally have reported that they also frequently monitor auditory cues at medication preparation zones and at the distributed nurse stations. On the other hand, 49% of the MedSurg-ICU nurses have reported that they rarely monitor auditory cues at the medication preparation zones. In both wards, they rarely monitor auditory cues at the supply rooms. In the MedSurg-ICU, the medication preparation and supply room spaces are separated by walls that extend from floor to ceiling. In the Neuro-ICU, the medication preparation areas are the extensions of corridors.



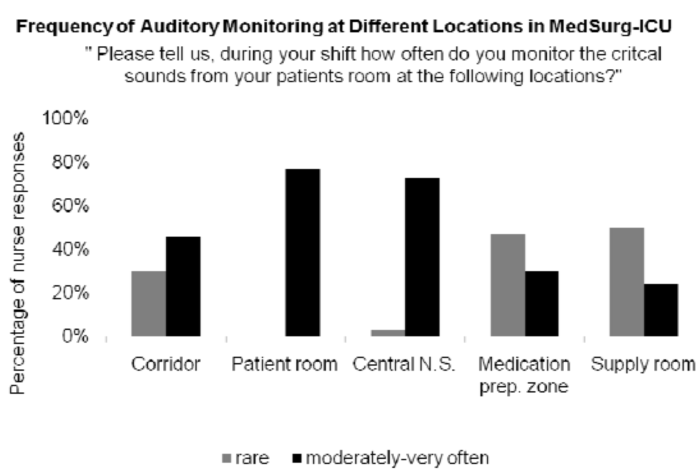


Figure 3.5 Frequency of auditory monitoring at different locations in the two ICUs

Auditory monitoring performance of nurses in MedSurg-ICU and Neuro-ICU

Nurses have been also questioned about their ability to recognize, hear, and localize auditory cues. As shown in Figure 3.6, the results vary. As shown in Figure 3.6a, the majority of the MedSurg-ICU and Neuro-ICU nurses “somewhat” or “completely” agree that they can hear the critical sounds in the unit. This percentage is somewhat higher in MedSurg-ICU but the difference is not significant.

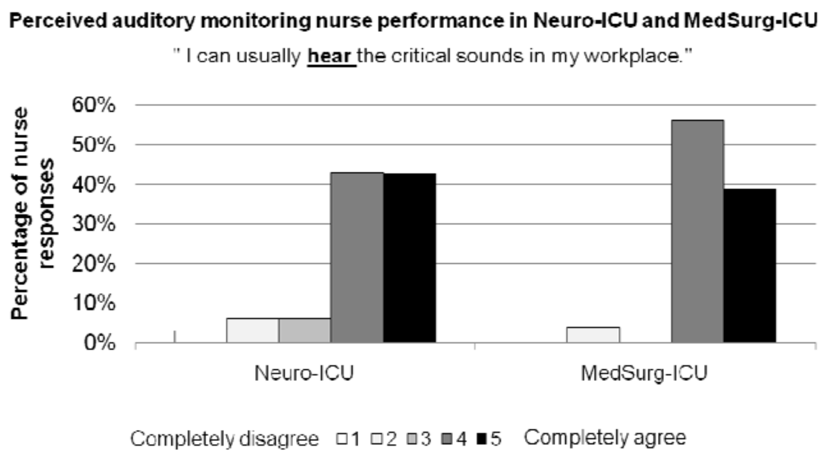
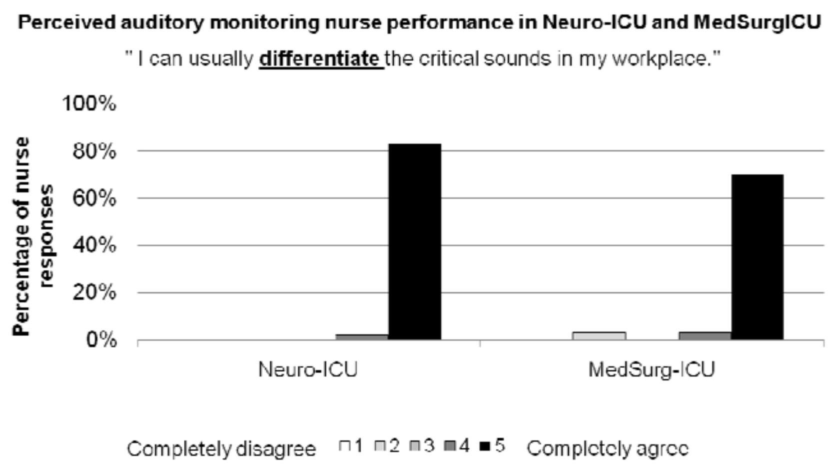
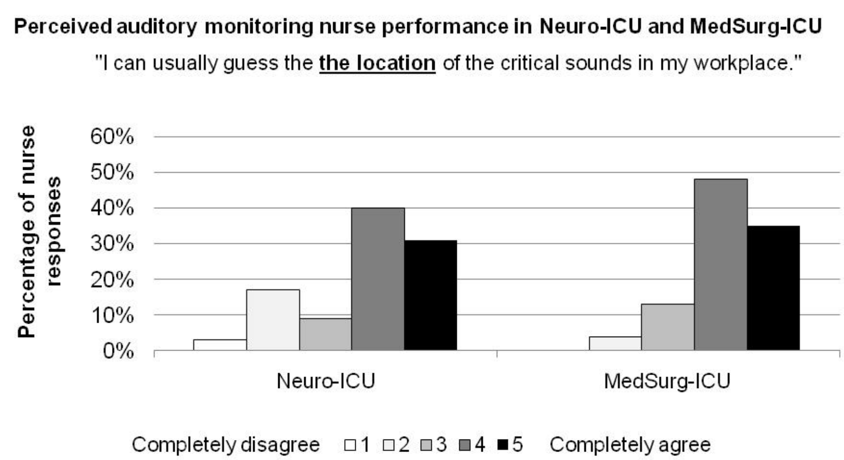


Figure 3.6 Perceived sound task performance of nurses in the two ICU`s: (a) ability to hear critical sounds (b) ability to differentiate critical sounds (c) ability to localize critical sounds

Figure 3.6 continued





Also as shown in Figure 3.6b, the majority of nurses “completely” agree that they can differentiate the critical sounds in the unit. This percentage is slightly higher in the Neuro-ICU. As shown in Figure 3.6c, the majority of nurses “somewhat” or “completely” agree that they can guess the location of the critical sounds in the unit. In the MedSurg-ICU, sound localization performance of nurses is slightly higher. However the differences between the perceptions of the nurses in the two units are not significant.

To summarize, hearing and sound localization are perceived to be somewhat higher in the MedSurg-ICU, but differentiation is perceived to be somewhat higher in the Neuro-ICU. The differences in perception might be related to unit architecture. As summarized in previous sections, sound localization performance is mainly related with background noise levels and reverberation time. As discussed earlier, the overall noise levels are the same in each unit, although the MedSurg-ICU has been found to be more "peaky." However, the MedSurg-ICU is a more compact unit and the reverberation time was measured to be lower. It is possible that the more compact setting and lower reverberation time of the MedSurg-ICU led to the improved ability of nurses hear and localize sounds, despite unit being more "peaky". The reason for the difference in differentiation perception between the two wards is less clear; one hypothesis is that the more "peaky" sounds in the MedSurg-ICU cause confusion when differentiating one alarm (which is a peak type of sound) from another.

Differences between RT30 in MedSurg-ICU and Neuro-ICU

To compare the length of the reverberation time (RT30) in the two wards, impulse response measurements are conducted. Averaged RT30 in the corridors of the MedSurg-ICU ranges between 0.44 and 0.56s across different frequencies (Table 3.1). In one of the corridors, the RT30 is as low as 0.3s. In the patient room of the MedSurg-ICU, averaged RT30 (250 Hz- 4 kHz) is 0.5s.

Table 3.1 Distribution of averaged RT30 across frequency measured in the corridors and in the unoccupied patient rooms in the two ICUs

		250Hz	500Hz	1kHz	2kHz	4kHz
Neuro-ICU	corridor	0.73	0.75	0.87	0.82	0.7
	patient room	1	0.77	0.71	0.77	0.76
MedSurg-ICU	corridor	0.56	0.5	0.52	0.54	0.44
	patient room	0.83	0.34	0.81	0.28	0.25

In the Neuro-ICU corridors and unoccupied patient rooms reverberation times are higher compared to RT30 measured in the MedSurg-ICU. Averaged RT30 in the corridors of Neuro-ICU ranges between 0.70 and 0.87s across different frequencies. In one of the corridors the RT30 is as high as 0.92s and the lowest RT30 measured in different corridors is 0.65s. In the patient room of the Neuro-ICU, averaged RT30 (250 Hz-4 kHz) is 0.8s. Given these values, the difference between reverberation times in the Neuro-ICU and MedSurg-ICU are perceptible based on ISO/DIS 3382-1 standards (Bork, 2000).

3.2.4 Discussion

Factors that impact the effectiveness of auditory monitoring performance of nurses particularly in ICUs have not been investigated as much as visual patient monitoring. This chapter provides a comprehensive overview of the factors related to auditory monitoring, including previous research related to the topic. Additionally, results from a case study examining nurses` perception of auditory monitoring in two ICUs are presented.

In the case study, ICU nurses strongly agree that auditory monitoring is highly important for patient safety in addition to visual monitoring. In addition, nurses ability to hear, differentiate, and localize auditory cues are also perceived to be critically important for patient safety. However, previous research shows that these sound tasks are hard to accomplish in complex sound environments. Hospital sound environments are extremely complex as they are multi-source, noisy, and most times reverberant in nature. Previous research indicates that particularly in highly reverberant spaces, sound localization can be very challenging. High background noise levels can also potentially negatively affect the detection of target sounds. Furthermore, the human auditory system has limited monitoring capabilities. Pushing the limits of the auditory system to monitor high number of sound events can require excessive efforts, in particular for novice nurses.

In the case study, interesting differences are found when comparing the importance of different ICU sounds for patient safety. Some of the alarm sounds are perceived to be more important than others. Specifically, the majority of nurses believe that medical ventilator alarms and patient monitor alarms are very important for keeping patients safe. A considerable percentage of nurses also believed that nurse call, feeding pump, and IV-pump alarms were critically important for patient safety.

Additionally, it is found in the case study that nurses listen to the auditory cues from different key locations in the critical care units. Some of those key locations include: patient rooms, nurse stations, and corridors. It needs to be noted that all these spaces are all connected through corridors. In the Neuro-ICU where the medication room is also connected to the corridors, it was also reported as a listening location. On the other hand, since in both units` supply rooms are separated from the corridors with walls from floor to ceiling, they are not reported as listening locations. Considering these results, the connectivity of spaces with corridors might be a significant indicator of key listening locations.

By comparing nurses` ability to conduct sound tasks in the case study MedSurg-ICU and Neuro-ICU, an interesting conclusion regarding effective environmental factors for auditory monitoring emerges. Apparently, nurses` perceived hearing and localization performance is higher in the MedSurg-ICU compared to the Neuro-ICU even though the Neuro-ICU is installed with high performance absorptive acoustic ceiling tiles and the MedSurg-ICU was found to be more "peaky". Parallel to nurse perceptions, RT30 levels (based on impulse response measurements) in the corridors and in the patient room are perceptibly higher in the Neuro-ICU compared to MedSurg-ICU. This indicates the potential significant impact of different design features on task supportive sound environments such as spatial design features associated with RT30 levels in addition to absorption qualities of materials. To systematically assess suggested relationships between different design features and reverberation time, more controlled follow up studies are also conducted. The study results are introduced in the following sections.

Overall, lack of proper monitoring of auditory cues can potentially delay the nurses` rescue efforts by disabling the early detection of complications, and could result in serious patient injury and even death. For effective auditory monitoring in hospitals, both environmental acoustic (e.g., reverberation time, overall noise levels) and sound source specific (e.g. acoustic qualities of sounds, number) solutions should be researched and adopted.

CHAPTER 4

ACOUSTICS OF ARCHITECTURAL SPACES: A LITERATURE REVIEW

Chapter 3 demonstrated that acoustic qualities of hospital sound environments can have significant impact on vital sound tasks (patient auditory monitoring) conducted by caregivers. Previous research indicates that design features of architectural settings such as floor-plate shape qualities can impact acoustic qualities of the built environment. This chapter provides an overview of the previous literature liking design and acoustics, acoustics parameters used in room-acoustics research and sound behavior in proportional and non-proportional spaces.

4.1 ROOM ACOUSTICS

The human auditory system is capable of differentiating the acoustic qualities of the sound produced inside and that produced outside an enclosed space (Mehta et al., 1997). Sound produced inside a room bounces back and forth from boundary surfaces. On the other hand, sound generally travels freely away from the source outdoors, unless major reflecting surfaces are present. Characteristics of an enclosed space such as volume, spatial proportions, floor-plate shape, and material qualities of boundary surfaces significantly affect the sound qualities and sound levels. This field of acoustic research exploring the sound behavior in enclosed spaces with different design implications is known as "room acoustics".

4.2 ROOM ACOUSTICS PARAMETERS

Acoustic measures used in the analysis of *rooms* are called room-acoustics parameters. For this chapter, room-acoustics parameters can be grouped in two categories: reverberation time (RT) and other room-acoustic metrics including sound strength (G), clarity (C), definition (D), early decay time (EDT), lateral fraction (LF/LFC) and centre time (Ts). Reverberation time has been a well-established room-acoustics parameter widely used in architectural acoustics for the assessment of various types of architectural spaces including music halls, hospitals, worship places and more recently in long enclosures. With the developments in perceptual acoustic research (known generally as "psychoacoustics"), additional room-acoustic parameters were proposed to assess different subjective attributes of sound quality, particularly in concert halls. The motivation was to identify and quantify different aspects of the overall acoustic quality of the music halls that are important for listeners' perception. Detailed information about the room acoustics parameters relevant to this chapter can be found in the "Definition of Term" portion of the appendix (Appendix A).

4.3 ACOUSTICS OF PROPORTIONAL SPACES

4.3.1 Sound behavior in rooms

This section reviews sound propagation theories and empirical data presented in the previous research.

The classic sound propagation theory (a.k.a diffuse field theory) was developed to predict the behavior of sound in concert halls. According to this theory, direct sound becomes negligible approximately after 10m (19.6ft) (a.k.a. “reverberation radius” or “critical distance”) (Galindo et al., 2005). At the critical distance, sound energy of the direct and reverberant sound fields are equal. After this point acoustic qualities are mainly defined by volume and RT. Additionally, empirical data shows that reverberation time in rooms does not vary much by distance or the position of the receiver (Abdou, 2003; Lundeby & Vigran, 1999; Pelorson, Vian, & Polack, 1992).

4.3.2 Floor-plate design and acoustics

Floor-plate design qualities of architectural settings can have a significant impact on acoustic qualities of sound environments. Previous studies linking floor-plate design and acoustics took place mainly in the concert halls as discussed in the following section.

Since the 18th century, concert hall floor-plates took a variety of different shapes. Typical concert hall floor-plate shapes include shoebox (rectangular), fan-shape, vineyard and horseshoe (Figure 4.1) (Barron, 1993).

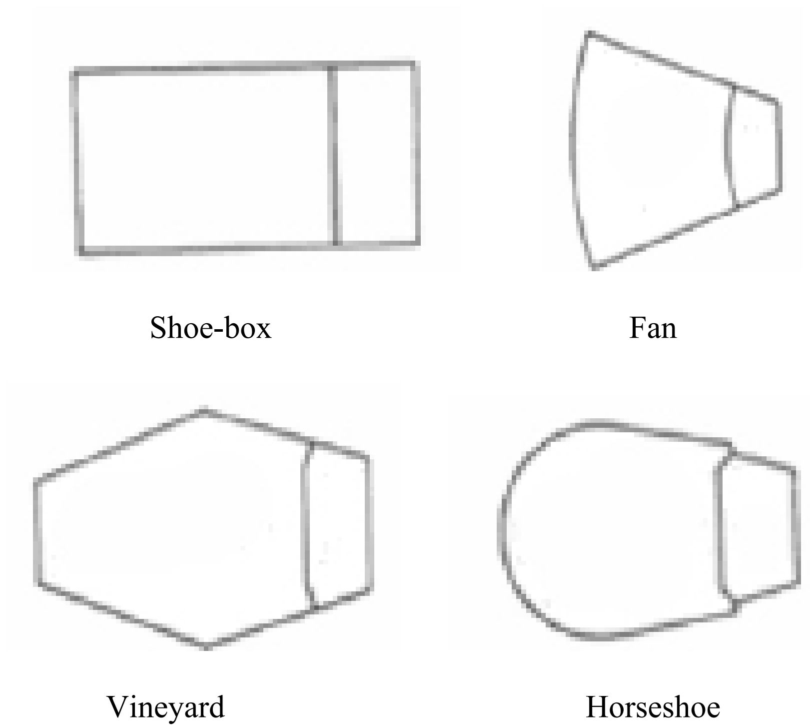


Figure 4.1 Commonly applied concert hall floor-plate shapes (from Barron, 1993)

There are also concert halls with elliptical floor-plate shapes but not many. One of the reasons is that elliptical floor-plates focuses sound at the centers of the geometry. This focusing effect leads to non-uniform distribution of sound energy and generates an unwanted focal effect (Cox & D'Antonio, 2009). A rare successful example of this type is Royal Albert Hall which required many efforts from acousticians (Figure 4.2) (Zhang, 2005).

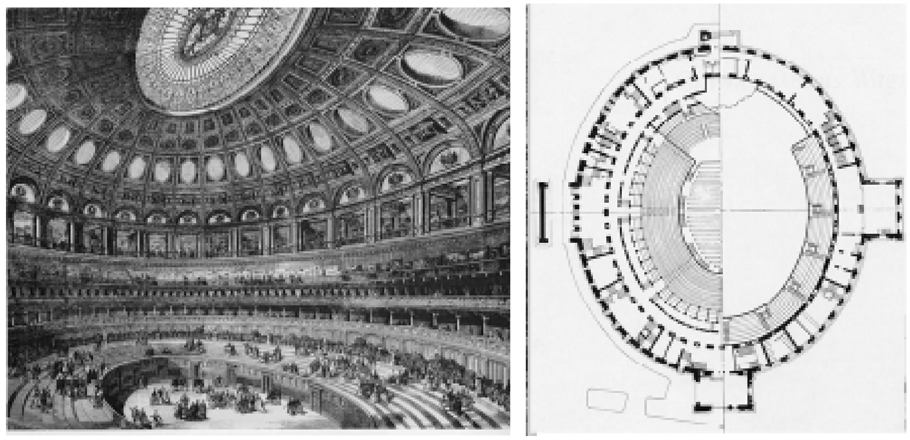


Figure 4.2 Royal Albert Hall with elliptical floor-plate shape (from Zhang, 2005)

Concert hall floor-plate shapes can also influence qualities of lateral sound (i.e., reflections coming from the side walls). Early lateral reflections contribute to the feeling of “spaciousness” in concert halls. “Spaciousness” is a desired sound quality specifically in concert halls. Findings of recent studies indicate that parallel and narrow walls of shoe-box concert halls with rectangular floor-plate shapes improve the early lateral reflections (Mehta et al., 1999). This is a primary factor explaining the successful acoustic performance of many shoe-box shaped concert halls. Beranek and Hann surveyed acoustic qualities of various concert halls (Hann, & Fricke, 1995). According to their findings, two thirds of the concert halls rated as “excellent” were in the shape of shoebox. A well known example is Boston Symphpny Hall (Figure 4.3).

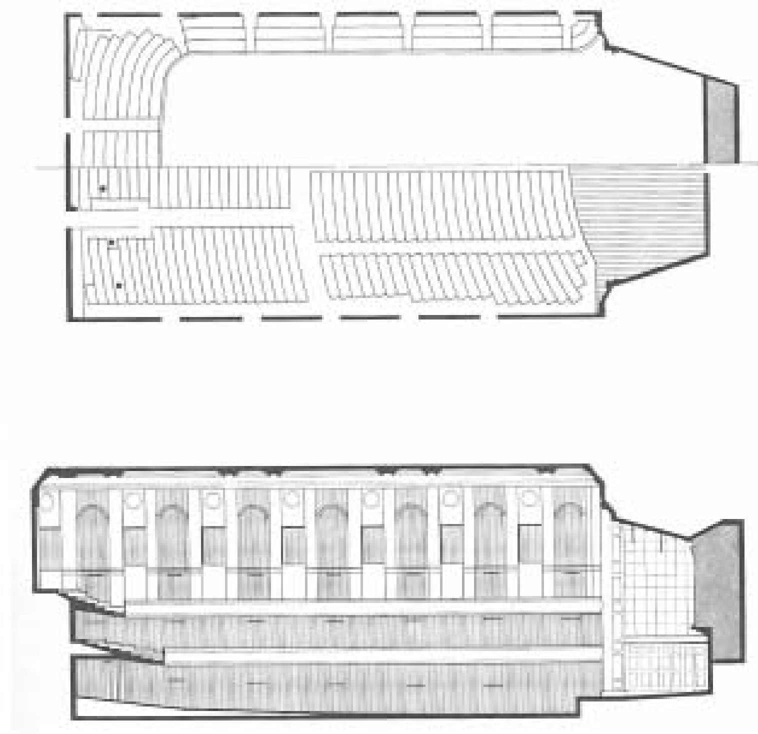


Figure 4.3 Boston Symphony Hall with rectangular floor-plate shape (from Hann, & Fricke, 1995)

Developments in acoustic technology and scientific knowledge enabled the application of more complex floor-plate shapes such as vineyard since the beginning of the 20th century. In vineyard floor-plates, a concert hall is subdivided into smaller audience zones surrounded by side walls. This type of design improves sound quality by providing lateral reflections. The Berlin Philharmonic is one of the most successful modern concert halls with vineyard floor-plate shape (Figure 4.4, Mehta et al., 1999).

Figure 4.4 Berlin Philharmonie Concert Hall with vineyard floor-plate shape (from Mehta et al., 1999)

4.3.3 Statistical analysis of floor-pate design and acoustics

The previous section introduced typical floor-plate shapes applied in concert halls. Several studies statistically and systematically analyzed the impact of floor-plate design qualities on acoustic outcomes in the concert halls. This section reviews the findings of these scientific studies.

Early studies indicated the significant impact of hall width in predicting sound qualities in concert halls (Gade, 1990; Klosak & Gade, 2008; Schroeder, Gottlob, & Siebrasse, 1974). Gade (1990) conducted impulse response measurements in 32 European halls and statistically analyzed the relationship between room-averaged acoustic data and design variables. By comparing the expected (based on classic sound propagation theory) and measured results, the study concluded that volume and reverberation time are the two main factors affecting new room-acoustic parameters such as reverberance and clarity. This finding supports how well the classic theory predicts acoustic conditions (e.g., EDT, C, L) of the concert hall as a function of RT and volume. The study also indicated the significant impact of floor-plate shape on clarity. Based on regression analysis results, the study found that clarity is positively correlated with hall width and angle between side walls. In other words, clarity is expected to be higher in wide/ fan-shaped walls compared to narrow/rectangular halls. The interpretation is that wider rooms tend to minimize the distance between source and receiver and increase the seating capacity of the halls and splayed side walls directs the early sound energy to the rear of the room (Mehta et al., 1999). Gade (1990) also found a fairly high correlation between hall width and LEF (r=0.73). The regression equation suggested by the study is included below.

$$LEF = 0{\cdot}47 - 0{\cdot}0085 \text{ width}$$

Schroeder, Gottlob, and Siebrasse (1974) correlated subjective perception with objective design and acoustic parameters (i.e., volume, width, time delay, reverberation time, definition and inter-aural coherence) of 11 European concert halls by conducting statistical analysis. For the subjective evaluations, a pre-recorded signal was played in each hall and re-recorded at the receiver locations with the use of an artificial head. Acoustic parameters were obtained from measured impulse response at the artificial head`s ears. Subjective evaluation of the recorded signals took place in an anechoic chamber. According to statistical analysis results, reverberation time (positively), inter-aural coherence (negatively), volume (negatively) and width of the halls (negatively) were significantly correlated with subjective “consensus preference factor”. Additionally width was negatively correlated with reverberation time. These findings indicate the acoustical disadvantages of larger halls.

A recent study used acoustic simulations and generated various theoretical design models to analyze the association between floor-plate shape and acoustic characteristics of shoebox-shaped concert halls (Klosak, & Gade, 2008). In total 24 theoretical models were generated, as shown in Figure 4.5. Only two design variables were changed among those theoretical models: a) volume and b) length-to-width ratio. The floor-plate shapes of the theoretical models ranged from square to elongated rectangle as shown in Figure 4.5.

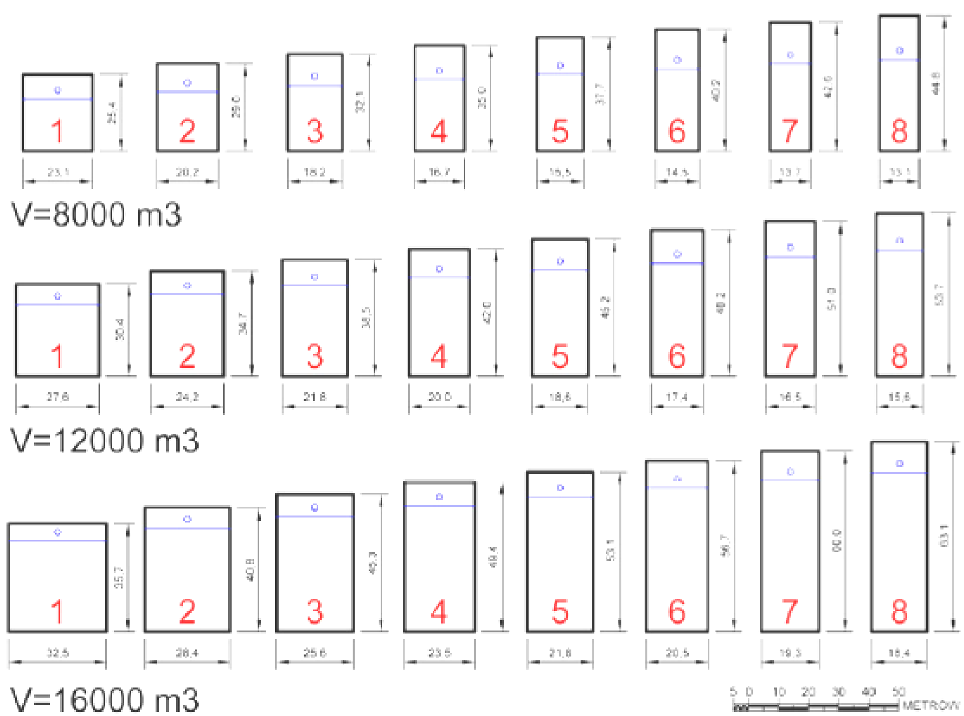
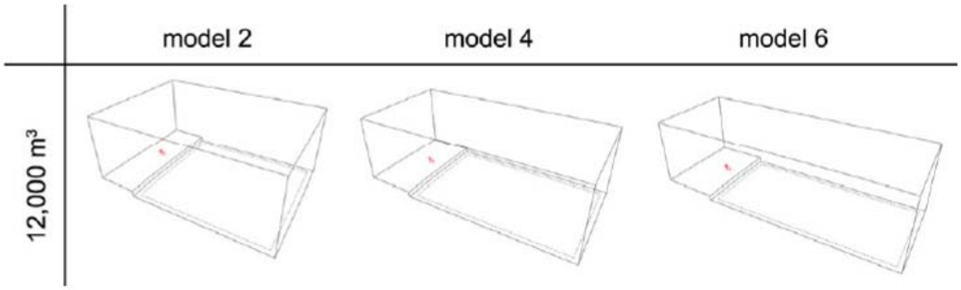


Figure 4.5 Floor-plate shapes of theoretical design models (from Klosak, & Gade, 2008)

Figure 4.5 continued



Acoustic simulation results calculated for 24 theoretical models indicated that uniformity of the distribution for sound quality metrics such as clarity (C_{80}) and strength (G) decreases as the shape gets more elongated. This was particularly true in the rooms with smallest volume ($8000m^3$). Similar results were observed for increasing volume. The study also highlighted the impact of both width and length in predicting lateral fraction (LF). Among theoretical models with similar L/W ratio, as the width increased LF values (i.e., the amount of the useful reflections arriving from the side walls) decreased. The study suggested the following regression equation showing the relationship between length-to-width and early lateral energy fraction (LF).

$$LF_{80} = 0.22395 + 0.39148 * e^{\frac{-L}{W*1.03755}} - W * \left(0.00193 + 0.01081 * e^{\frac{-L}{W*0.6763}}\right)$$

To summarize, various studies analyzed the association between floor-plate design qualities and acoustic outcomes and found statistically significant relationships. Even though these studies were particularly conducted in concert halls and correlated the design features and acoustic parameters more specific to concert halls, their findings in general underline the association between floor-plate design and acoustics.

4.4 ACOUSTICS OF NON-PROPORTIONAL SPACES

4.4.1 Sound behavior of long spaces

Long enclosures are considered as non-proportional spaces related with their extreme spatial proportions. Examples of long enclosures are corridors and underground train stations. Acoustics of these non-proportional spaces differ from the acoustics of more traditional rooms. Principles of *classic sound propagation theory* and researched relationships between *room* design features and acoustics do not necessarily apply to non-proportional spaces. The following section defines the differences between sound environments of proportional and non-proportional spaces and introduces the sound behavior characteristics in long enclosures.

Classic theory assumes the existence of diffuse field and uniform distribution of the sound rays in all directions (Kang, 2002b). In proportional spaces where a sufficiently diffuse sound field exist (e.g., concert halls), beyond the reverberation radius, the contribution of direct sound becomes negligible; therefore, SPL is considered to be approximately constant. Similarly, reverberation time based on Eyring and Sabine formulas is considered to be the same at any point in the room beyond the reverberation radius. On the other hand, sound field in long enclosures is not uniformly diffuse related with the non-proportional/extreme dimensions. It is one of the key reasons why sound behavior in long enclosures is quite different compared to sound behavior in the sufficiently diffuse sound fields found in more traditionally-shaped rooms.

Various studies have been conducted to analyze the behavior of sound in long enclosures with rectangular floor-plate shapes. The main goal of these studies was to explain how different qualities of sound vary by distance and long enclosure design features (e.g., cross section size). The majority of the studies systematically documented acoustic qualities of long enclosure sound environments (e.g., sound attenuation, early decay time and reverberation time) by conducting impulse repose measurements at changing distances from the sound source. In the following sections, the findings of these studies are introduced.

4.4.1.1 Field measurements

Kang (2002c) conducted field measurements in different long enclosures including a corridor and multiple underground stations with rectangular floor-plate shapes. These field studies primarily explored the changing sound behavior with distance. The length, width and height of the corridor were 42.5m (139ft), 1.56m (5.2ft) and 2.83m (9.3ft) respectively. The boundaries of the corridor were geometrically reflective and average absorption was low (approximately 0.1 at 500Hz and 1 kHz). The results of the field measurements conducted at different distances from the sound source are shown in Figure 4.6 below. Overall, reverberation time results measured at different receiver locations increases with increasing source-receiver distance.

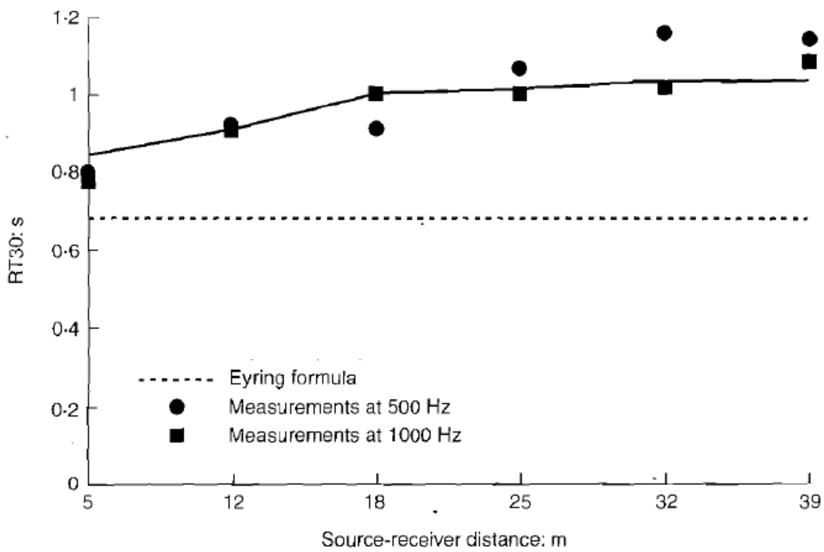


Figure 4.6 Spatial distribution of reverberation times in a single corridor (from Kang, 2002c)

The underground stations studied by Kang (2002c) were deep tube stations with circular cross-sectional shape (named Old Street, Warren Street and St John`s Wood). The results of the field measurements conducted at different distances from the sound source are shown in Figure 4.7 below. As the source and receiver distance increases, the reverberation time and early decay time increase along the length until about 40m (131ft) and then become approximately stable or decrease slightly. In general reverberation time values were greater than early decay time values, indicating that sound decay curves of these long enclosures are not linear.

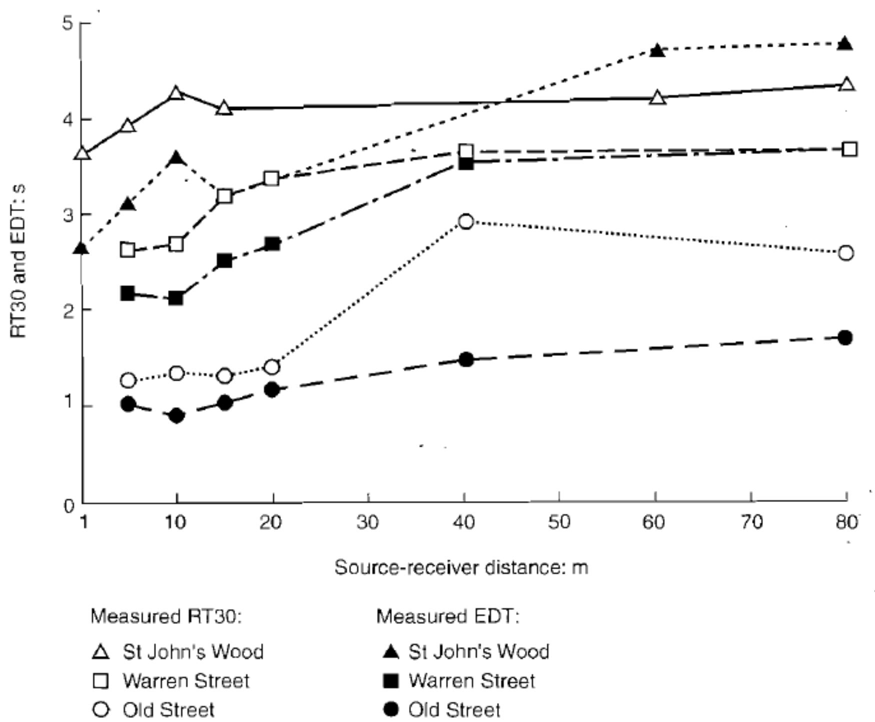


Figure 4.7 Spatial distributions of RT30 and EDT levels in tunnels (from Kang ,2002c)

4.4.1.2 Simulation studies

The number of studies exploring the association between design and acoustics of long enclosures remains limited. Kang conducted a series of detailed computer simulation studies to systematically assess the impact of different design factors on acoustics of long enclosures (Kang, 2002c; Kang, 2002d). In these theoretical studies, mainly the design and acoustics of long enclosures with rectangular floor-plate shapes (e.g., single corridors) were analyzed. Related with the focus of this thesis, the following section is limited to studies exploring the impact of long enclosure designs on reverberant qualities. More detailed information about the relationship between long enclosure design and sound attenuation can be found in Kang (2002).

Design factors affecting reverberant qualities of long enclosure sound environments

Different design factors can affect length of reverberation time in long enclosures such as corridor length, absorptive qualities of the surface materials, sound source type and cross section dimensions. Kang conducted various computer simulation studies to systematically assess the impact of design features on length of the reverberation time in long enclosures (2002c).

A set of theoretical models were generated to assess how reverberation time varies along the corridor length in long enclosures with different absorption coefficients (Figure 4.8). Long enclosures with 6mx4m (20ftx13ft) cross section were assigned two absorption coefficients: 0.1 and 0.2. The boundaries of the long enclosures were geometrically reflective. For the less absorptive case ($\alpha = 0.1$), reverberation time values increased rapidly until a maximum and then decreased very slightly in the long enclosures. For the more absorptive case ($\alpha = 0.2$), reverberation time values increased less rapidly until a maximum and then decreased with a steeper slope as compared to the ($\alpha = 0.1$) case.

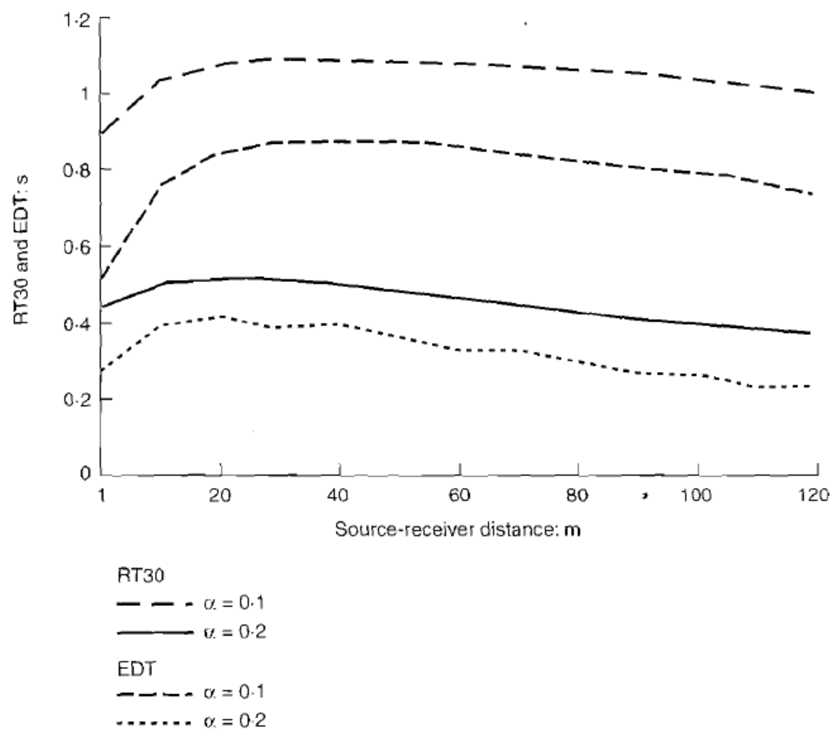


Figure 4.8 RT30 and EDT due to absorptive qualities of boundaries in long enclosures (from Kang, 2002c)

A second set of theoretical models were generated to assess the impact of diffusely and geometrically reflective boundaries on reverberation time values. Figure 4.9 shows interesting differences between behaviors of sound in these two long enclosures. In the geometrically reflective long enclosure, reverberation time increased slightly and then decreased slightly. Interestingly, in the diffusely reflective long enclosure, reverberation time consistently increased. Moreover, reverberation time values were generally 30-60% longer in the diffusely reflective boundaries case.

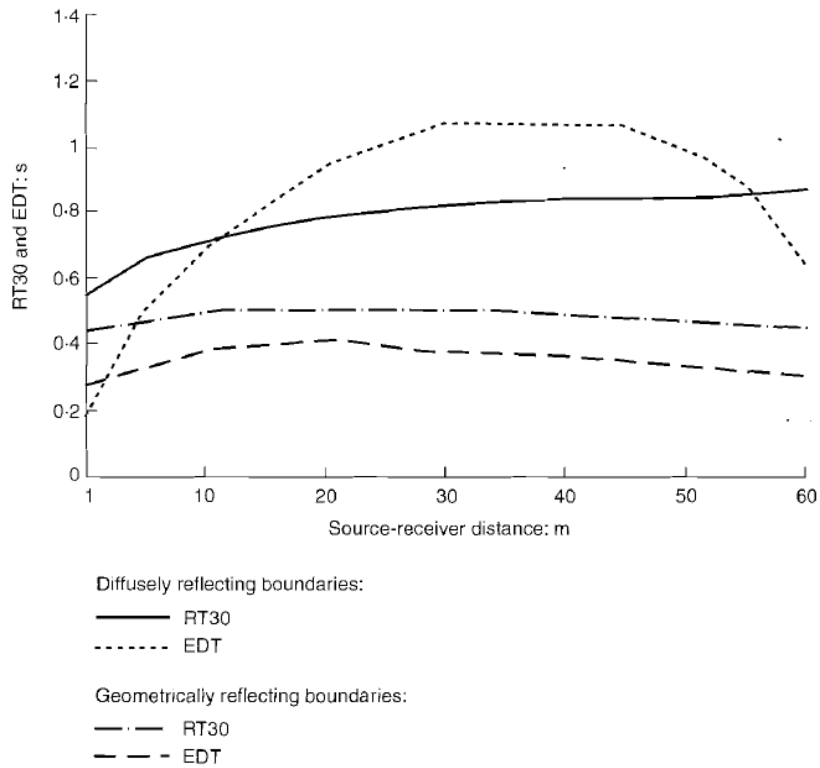


Figure 4.9 RT30 and EDT due to reflective qualities of boundaries (from Kang, 2002c)

A third set of theoretical models was generated to assess the impact of corridor length on reverberation time values (Figure 4.10). One of theoretical models was 60m (196ft) long and the other was 120m (394ft) long. The boundaries of both long enclosures were diffusely reflective and the end walls were open. Reverberation time values along the corridor length in the shorter case were about 20-30% less compared to the longer case.

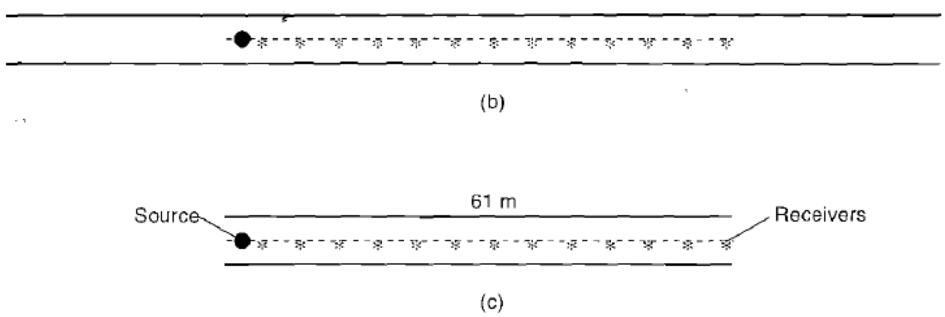


Figure 4.10 Floor-plans of two long enclosures with different length (from Kang, 2002c)

A fourth set of theoretical models was generated to assess the shape and size qualities of long enclosure cross sections on length of reverberation time in long enclosures with diffusely reflective boundaries. Theoretical models with 5 different cross sections (and thus different aspect ratios) were generated including 12mx8m (39ftx26ft), 16mx6m (52ftx20ft), 24mx4m (79ftx13ft), 6mx4m (20ftx13ft) and 8mx8m (26ftx26ft).The length of all models were 120m (393ft) and all surfaces were assigned an absorption coefficient of 0.2. As shown in Figure 4.11, for a given cross-sectional area, the reverberation time values could vary significantly with the aspect ratio. Reverberation time values become greater as the cross-section tends towards square. In addition, in the long enclosures with larger cross section, reverberation time values were longer. Similar results were observed for long enclosures with geometrically reflective boundaries.

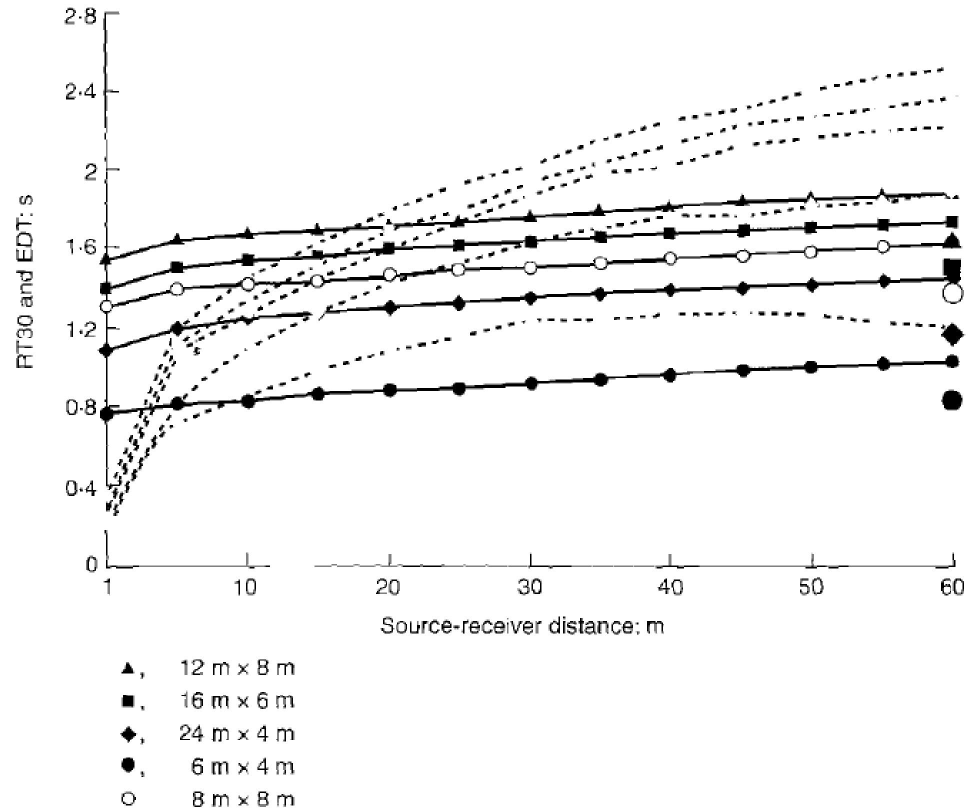


Figure 4.11 RT30 and EDT due to cross-sectional size (from Kang, 2002c)

A fifth set of theoretical models were generated to assess the distribution of boundary absorption in long enclosures with diffusely reflective boundaries. Theoretical models had constant amounts of absorption with five different distributions ranged from evenly distributed absorption in cross section (D1) and one boundary strongly absorbent and the rest is reflective (D5). From D1 to D5 the reverberation time values decreased continuously and the variation was about 30%. Reverberation time was the longest with absorption that is evenly distributed in cross section and the shortest when one boundary was highly absorbent.

Kang also systematically analyzed the impact of street design on length of the reverberation time and other acoustic outcomes such as sound attenuation by conducting computer simulations (2002d). Similar to other long enclosure types, in the urban streets with rectangular floor-plate shape, reverberation time increased systematically with increasing distance between source and receiver. Similarly, reverberation time values also increased significantly with increasing the building height.

4.5 ACOUSTICS OF LONG SPACES WITH BRANCHES

The previous section reviewed the findings of theoretical acoustic studies conducted in long enclosures with rectangular floor–plate shapes. There are very few studies that have documented the behavior of sound in more complex long enclosures, such as interconnected long enclosures with complex floor-plate shapes (e.g., long enclosures with branches). The following section reviews the findings of the studies conducted in interconnected long enclosures with complex floor-plate shapes.

Abel et al. (2008) analyzed the association between design and acoustics of historical underground galleries used for ritual purposes by conducting field measurements. Underground labyrinthine galleries were arranged in a series of small rectangular alcoves off narrow corridors (Figure 4.12, Figure 4.13). Some of the other features of the galleries were rectilinear shapes, narrow width, short height and stone walls.

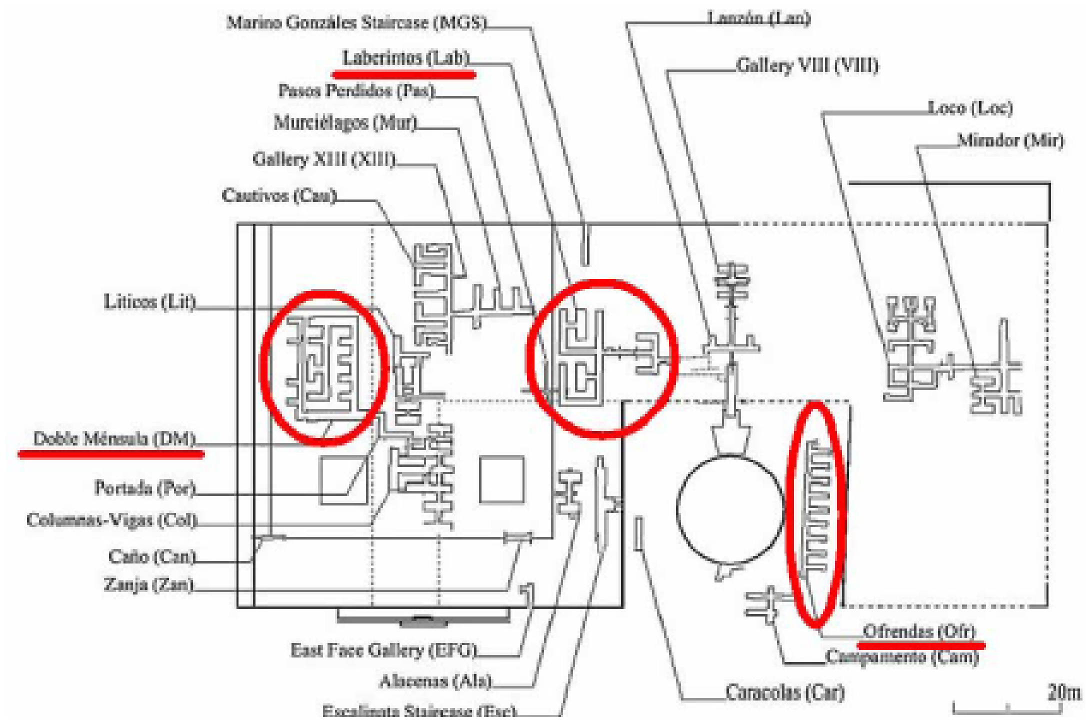


Figure 4.12 Site-plan of historical underground galleries (from Abel et al., 2008)

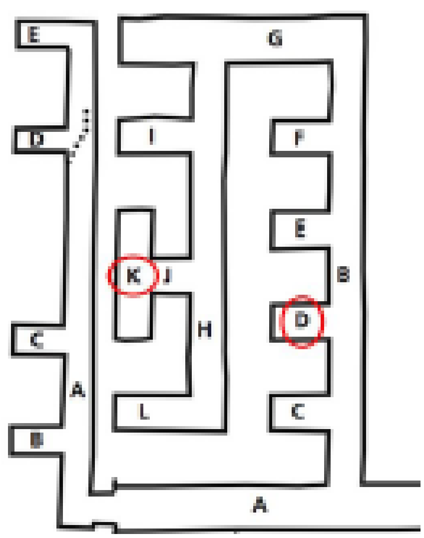


Figure 4.13 Floor-plan of historical interconnected underground galleries (from Abel et al., 2008)

Impulse response measurements were conducted at multiple different locations. As shown in Figure 4.13, location K is a representative receiver location located at one of the alcoves and D is a representative source location located at another alcove. Overall, in the underground galleries reverberation time was short (generally less than 0.5s) to enable the rhythmic sound of shell trumpets. Some other sound qualities include dense and energetic early reflections and low-inter-aural cross correlation. The study also found that number of turns (in the path between source and receiver) have significant impact on reverberation time. Increasing the number of turns between source and receiver led to higher reverberation time values. Reverberation time was shortest along straight lines between source and receiver.

Kang (2002d) systematically compared the sound fields in street canyons with different designs that incorporated a main street / side street configuration. A set of computer simulations was generated to assess how source location affects reverberation time. As shown in Figure 4.14, when the sound source moved to different locations in the main street with two side streets, a slight increase (10%) in average reverberation time levels was observed. Moreover, related with lack of direct sound, in the side streets reverberation time was systematically longer compared to the values in the main street.

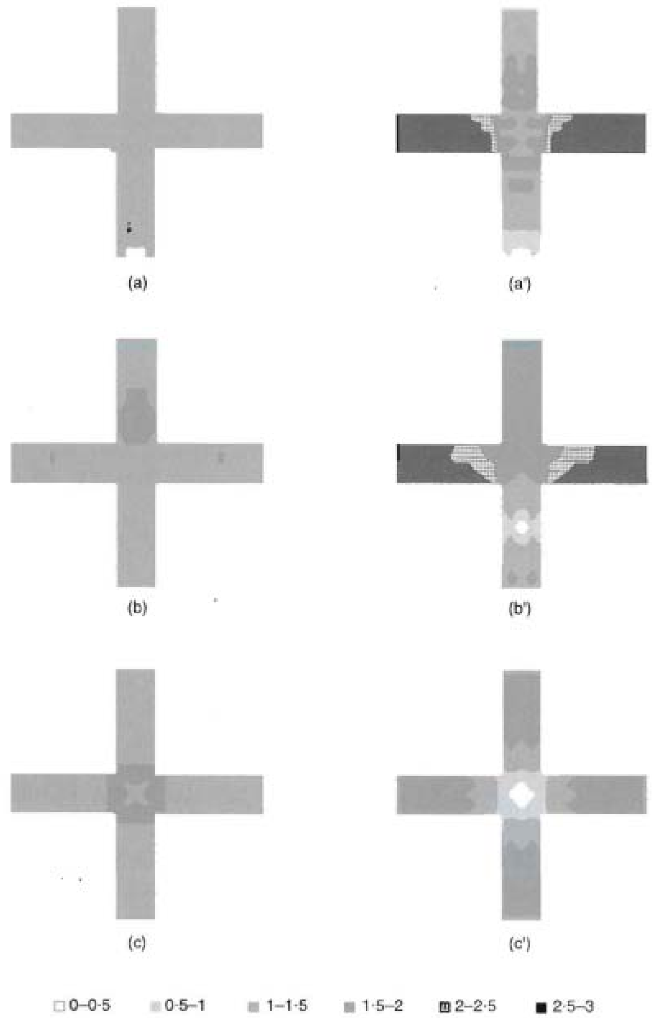


Figure 4.14 Spatial distribution of reverberation time (in second) along a “+” street junction (from Kang, 2002d)

Liu and Lu (2009a) compared the sound fields of straight long enclosures without any branch and the sound fields of the long enclosures with one branch (vertical, left inclined and right inclined) via 1:10 scale physical models (Figure 4.15). The dimensions of the full scale long enclosure were 94m-length (308ft), 7m-width (23ft) and 5m –height (16ft). However the characteristics of the branches such as length, width and angle were not the same.

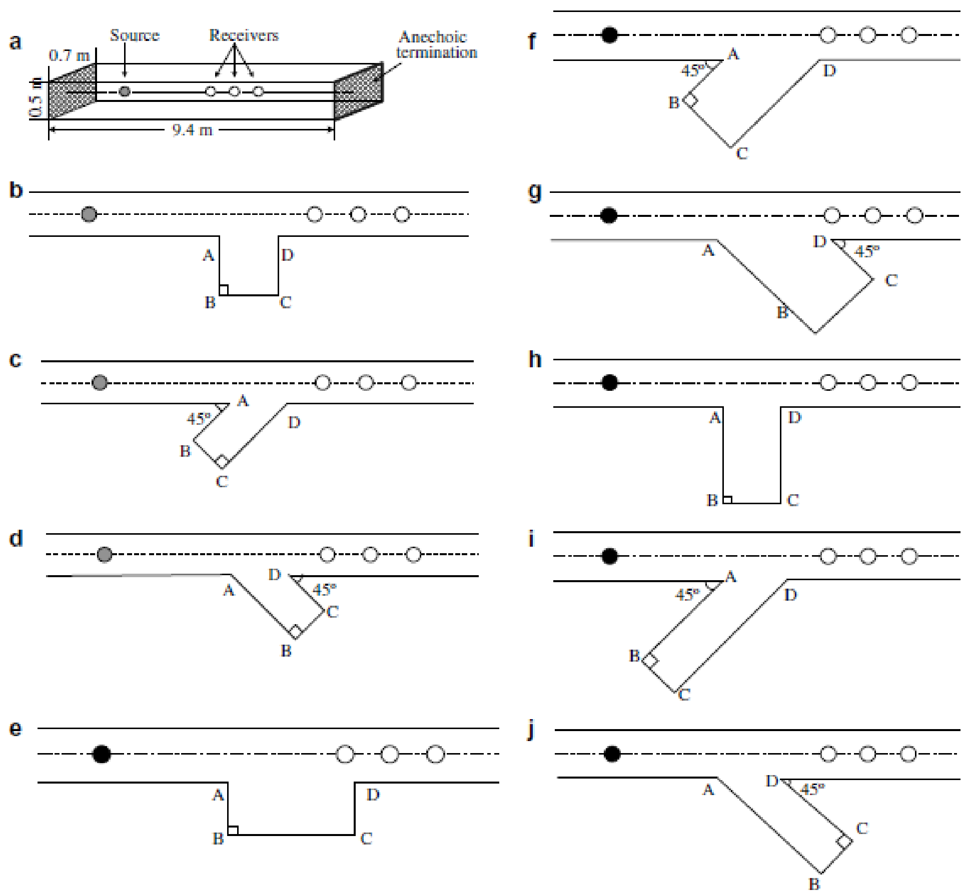


Figure 4.15 Floor-plans of theoretical long enclosures with a single branch (from Liu, and Lu, 2009a)

Reverberation time varied at different frequencies (Figure 4.16). For example at the low frequencies, RT30 was longest for the straight long enclosure, second longest for the long enclosure with a widened left inclined branch, third longest for the long enclosure with a left inclined branch and the shortest for the long enclosure with an extended left inclined branch.

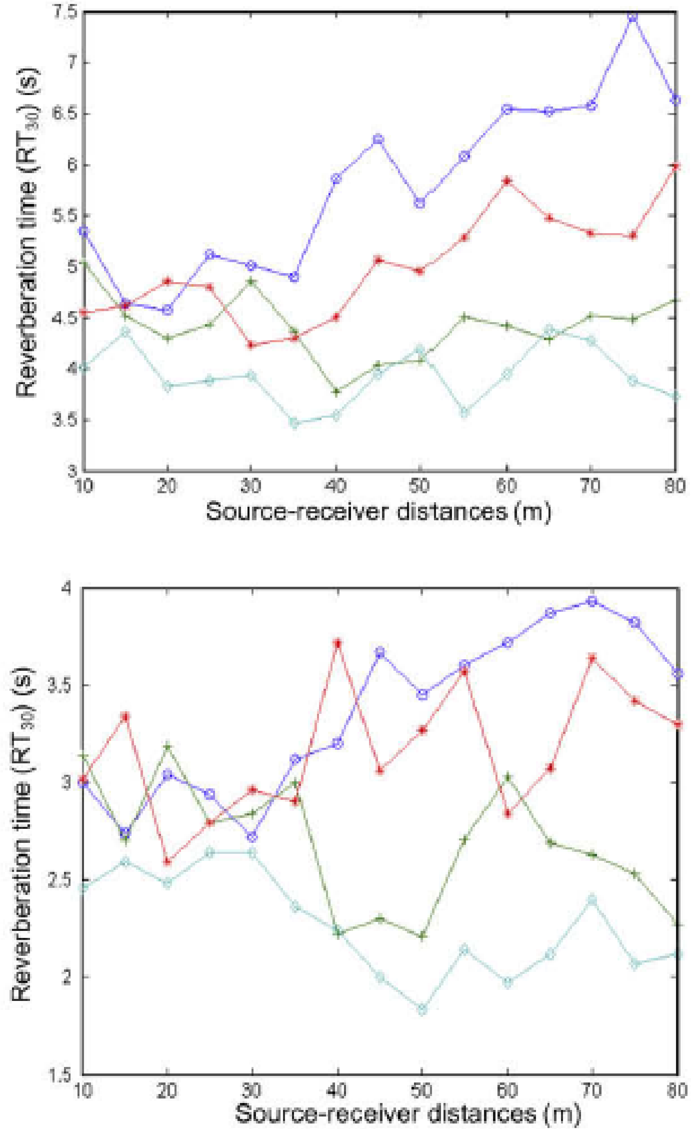


Figure 4.16 Distribution of RT30 in long enclosures with a single branch
(top): 500Hz; (bottom):1000Hz (from Liu, and Lu, 2009a)

Another study by Liu and Lu (2009b) analyzed the sound fields of long enclosures with multiple vertical or inclines branches via 1:10 scale physical models. The dimensions of the full scale long enclosure were 94m –length (308ft), 7m –width (26ft) and 5m-height (16ft). Sound source and receivers were arranged along the central line of the main enclosure (Figure 4.17).

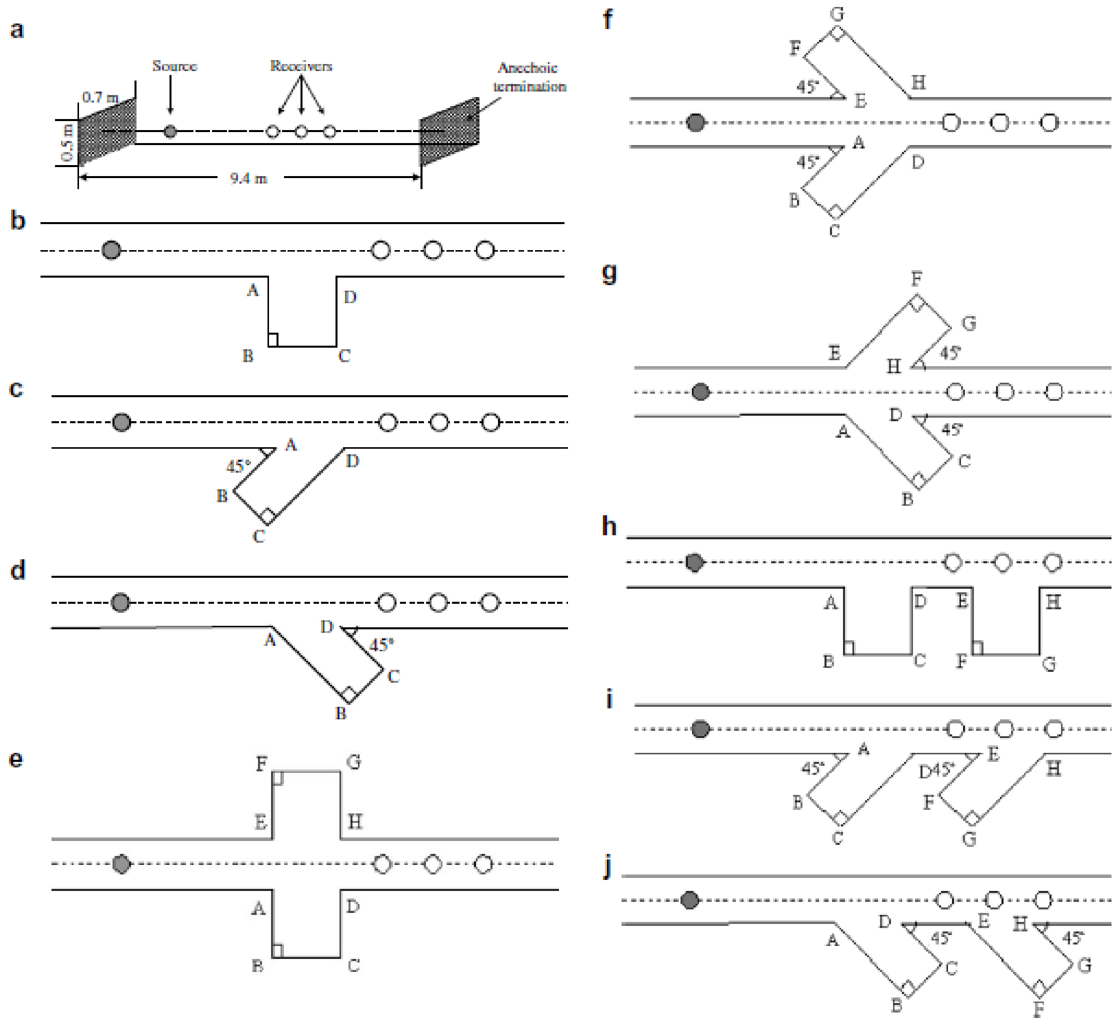


Figure 4.17 Floor-plans of theoretical long enclosures with multiple branches (from Liu, and Lu, 2009b)

RT30 values of long enclosures with multiple branches were frequency dependent (Figure 4.18) and frequency has little impact on RT30 levels in the enclosures with one branch. Long enclosures with multiple branches had lower RT30 levels compared to long enclosures with one branch and without any branch. In the low frequency range, orientation of the branches did not affect the results. However, in the high frequency range, orientation of the braches had a significant impact on RT30 values. Overall, the study findings indicated that sound field of a long enclosure with multiple branches is more complex and inhomogeneous compared to long enclosures without branches or with one branch.

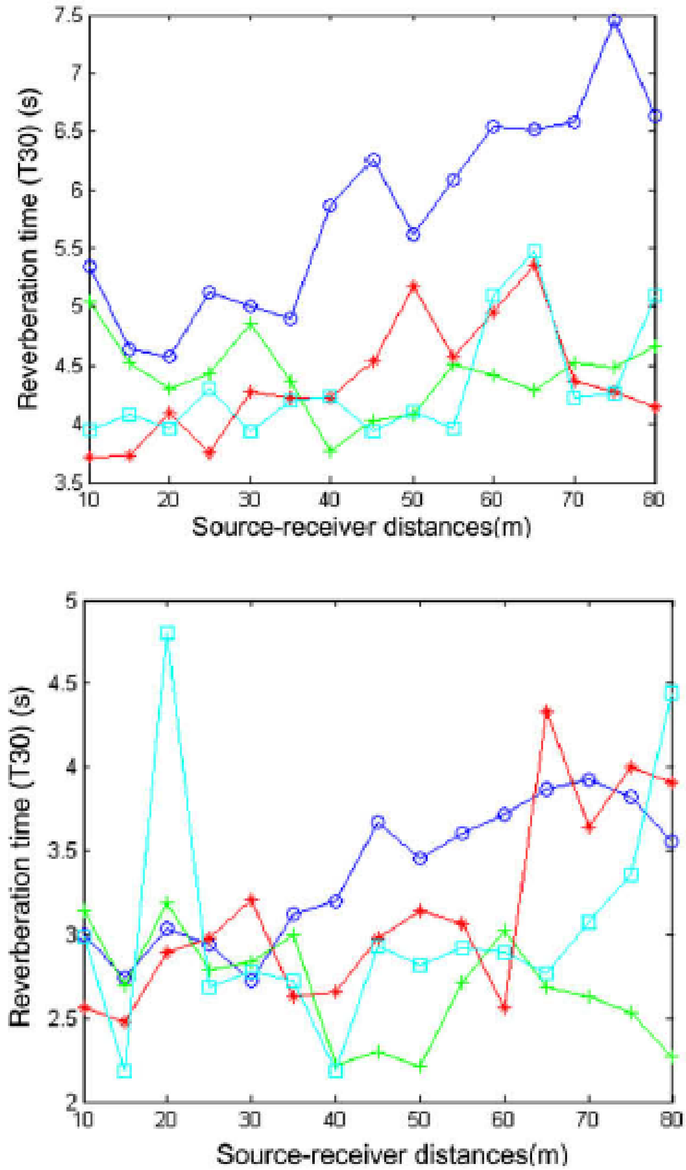


Figure 4.18 Distribution of RT30 in long enclosures with multiple branches (top): 500 Hz; (bottom):1 kHz (from Liu, and Lu, 2009b)

4.6 CONCLUSION

Reverberation time is a universal acoustic metric that has been used to assess the acoustic characteristics of various spaces including long spaces and rooms. Newer room-acoustic metrics were developed such as early decay time, clarity, sound strength to particularly assess the acoustic qualities of music halls that relate to audience experience. Even though some studies have documented the RT and EDT levels in long enclosures, there are still discussions whether the newer acoustic metrics are applicable for the acoustic analysis of long enclosures.

Related with the design qualities of spaces such as spatial proportions, the acoustic characteristics of their sound environments can vary significantly. Therefore acoustic theories applicable in one type of space (e.g., concert halls) might not be applicable in other types of spaces (e.g., corridors). For example, the principle of classic room acoustic theory that is generally valid in music halls is not necessarily applicable in long enclosures. Various studies have been conducted in the music halls and statistically analyzed the relationship between specific design characteristics of floor-plate shapes such as width, length and acoustic outcomes. However the findings of these studies are limited to more proportional shaped rooms and do not necessarily apply to long enclosures.

The number of studies conducted in long enclosures exploring the association between design and acoustics is growing. The acoustic conditions in long enclosures were studied via field measurements or computer simulations. Computer simulations enable the systematic analysis of the acoustic conditions in long enclosures. However most of those studies mainly considered straight long enclosures such as urban street or underground train stations. A few studies explored the reverberant qualities of long enclosures with complex floor-plate geometries such as underground stations with branches or staggered urban streets. However, very limited information exists on the acoustic conditions of inter-connected corridors located in the buildings. Dimensional qualities of building corridors differ from other long enclosures (e.g., underground stations, urban streets) which could potentially affect acoustic outcomes differently.

Overall, findings of long enclosure studies agreed that as the shape of the long enclosures gets more complicated, sound behavior in these settings also becomes highly complicated. However, more systematic research is necessary to clarify the impact of specific design features on acoustics of inter-connected corridors with complex floor-plate shapes.

CHAPTER 5

MEASUREMENTS AND SIMULATIONS OF THE ACOUSTICS OF LONG ENCLOSURES

The majority of the previous research has assessed the acoustic qualities of hospital sound environments by conducting field measurements. The use of acoustic simulation tools in healthcare acoustics is still not very common. It is probably because healthcare settings are composed of non-proportional spaces such as interconnected corridors as well as proportional spaces such as patient rooms. Various studies have tested the effectiveness of acoustic simulation tools in predicting acoustic qualities of proportional spaces such as concert halls and long enclosures with simple geometries (Kang 2002; Li, and Lu, 2004; Li, and Lu, 2005; Yang, and Sheild, 2004). However, the number of studies assessing the effectiveness of acoustic simulation tools in predicting acoustic qualities of non-proportional spaces particularly interconnected corridors still remains limited. This study tested the effectiveness of an acoustic modeling program that uses hybrid prediction method (*CATT-Acoustics V8*) in predicting acoustic qualities of complex long enclosures.

Accurate simulation of sound behavior is highly complex. Two key factors necessary for accuracy of acoustic predictions are: a) the overall prediction method adopted by the acoustic modeling developers, and b) modeling settings selected by the user. Appendix I contains more information on computerized acoustic modeling prediction methods, modeling settings and the findings of studies assessing the validity of computerized acoustic modeling tools.

5.1 EMPIRICAL STUDY 1

VALIDATION of CATT ACOUSTIC PREDICTIONS

Hospitals are composed of proportional and non-proportional spaces such as inter-connected spaces. Even though the use of an acoustic simulation program with hybrid prediction program has been validated for proportional spaces, its use for complex non-proportional spaces has not been validated. To assess the effectiveness of CATT acoustic simulation program in predicting the acoustic qualities of complex non-proportional spaces (i.e., interconnected spaces), empirical study 1 conducts series of validation studies in the actual inter-connected corridors. Previous study findings agree that ISM (Li, and Lu, 2005) and ray tracing methods (Yang, and Sheild, 2004) perform well in predicting the acoustics of long spaces. Hybrid methods incorporate the best features of ISM and ray tracing methods. However, the use of hybrid methods for acoustic analysis of long spaces has not been validated yet. In addition, particularly in complex settings, diffraction is one of the important factors that contribute to sound quality as well as reflection and absorption. However, not many acoustic simulation programs are capable of handling diffraction. CATT offers an *automatic edge diffusion function* to emulate diffraction from edge diffusion. The effectiveness of this feature and some other useful CATT features has not been tested yet in this context. CATT also offers an alternative prediction method other than corrected tail ray tracing method (RTC) to handle the late reflections effectively in complex geometries. By comparing the predicted (CATT) and measured (in situ impulse response) results, this study assessed the effectiveness of CATT-Acoustics in predicting the acoustic qualities of inter-connected corridor spaces.

5.1.1 L-shaped corridors

Methodology (L shaped corridor)

The first set of impulse response measurements has taken place in an L-shaped corridor. This corridor is located in an educational building from the 1960s on the Georgia Institute of Technology campus. The total volume of the L-shaped corridor is 397 m^3 (14,019ft^3). Its dimensional properties are as follows: height: 2.7m (8.8ft); width: 2.4m (7.8ft) and length: 60m (197ft). In total, the L-shaped corridor includes 31 doors and 18 windows. Figure 5.1 shows the location of the sound source and the receivers. Related with the focus of this study, the measurements have taken place only in the non-visual sound fields of the corridors. This study examines the association between design and acoustics. However, in the visual sound field, direct sound significantly affects the acoustic outcomes. To isolate the interfering effects of direct sound, this study only focuses on the sound behavior in the non-visual sound field.

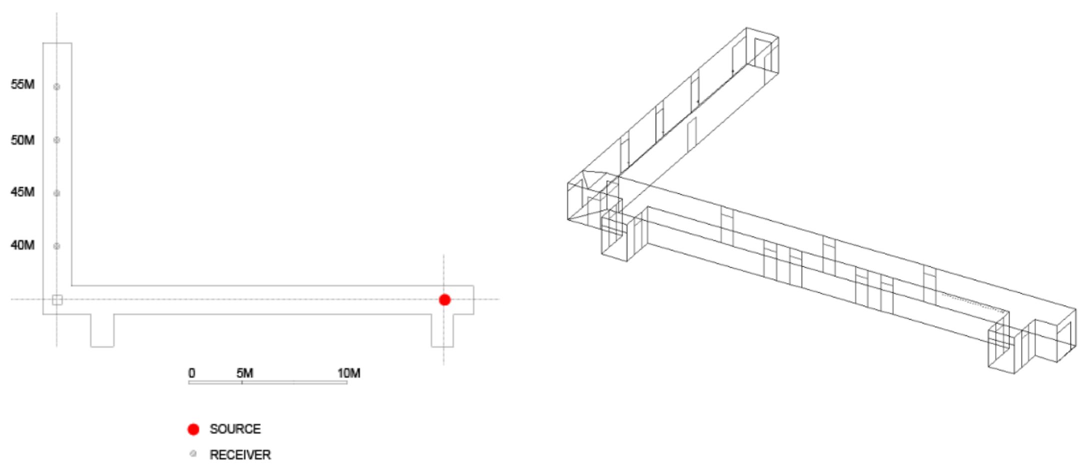


Figure 5.1 3D-CATT model and floor-plan of an L-shaped corridor

The same space is modeled with the use of CATT-Acoustics simulation program. Similar materials are assigned to enclosure surfaces and receivers are located at identical locations. Table5.1 shows the absorption qualities of materials assigned to the enclosure surfaces. Two types of ceiling tiles are used. The one represented as “medium absorption” in Table5.1 is gathered from Mehta et al. (1997). Idealized absorption coefficients are also used for the ceiling tiles represented as “low absorption” in Table5.1. The reason is that majority of the educational settings visited in this pilot study are more than 40 years old, damaged in some places, and more than likely they are not performing at the “medium absorption” level.

Table 5.1 Material absorption coefficients of the L-shaped corridor

Surface	**Material**	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**	**SC**
Door	Wood	0.21	0.10	0.08	0.06	0.06	A.E
Ceiling	Acoustic ceiling tile (low absorption)	0.38	0.38	0.38	0.38	0.38	20%
	Acoustic ceiling tile- (medium absorption)	0.33	0.54	0.69	0.69	0.56	20%
Floor	Vinyl on concrete	0.03	0.03	0.03	0.03	0.02	10%
Window	Glass	0.25	0.18	0.12	0.07	0.04	A.E
Wall	Painted concrete	0.05	0.06	0.07	0.09	0.08	30%

Findings (L shaped corridor)

Room-averaged predicted and measured reverberation time results across frequency are shown in Figure 5.2. When idealized low absorption coefficients are considered, the difference between measured and predicted results is lower. The “just noticeable difference”-(JND) for the room averaged reverberation time levels range between 0% and 20% as shown in Tables 5.2 and 5.3. According to ISO 3382 the differences as low as 5% are perceptible, but other sources show JNDs as high as 39% are perceptible (Meng, Zhao, & He, 2006). Appendix J contains additional information about JND for reverberation time. Regardless, the study findings are parallel overall to the findings of previous research. For example, the JND results are quite similar to those reported by Kang (2002) where he later used the validated acoustic simulation program for several theoretical studies conducted in long enclosures. Therefore, the findings of this section suggest the potential effectiveness of hybrid method in predicting the room-averaged reverberation time outcomes for L-shaped corridors. However, it needs to be noted that this validation analysis only took into account non-visual sound field.

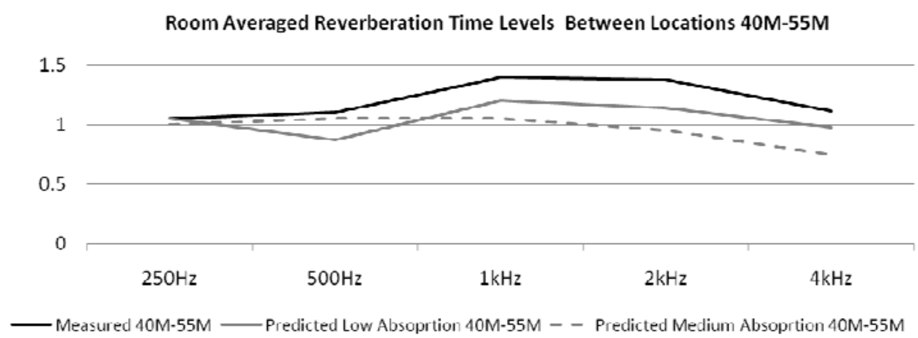


Figure 5.2 Room averaged measured vs. predicted reverberation time in an L-shaped corridor

Table 5.2 Just noticeable difference values for room averaged reverberation time (non-visual sound field)

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND (low abs)	0%	20%	14%	17%	12%

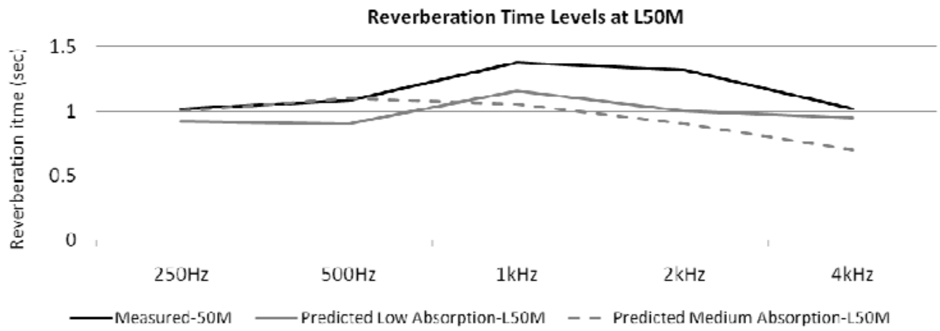


Figure 5.3 Measured vs. predicted reverberation times at the receiver location 164ft (50m) away from the sound source

Table 5.3 Just noticeable difference values for reverberation times measured at 164ft (50m) away from the source

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND (low abs)	10%	20%	18%	20%	7%

5.1.2 Race Track Corridor

Methodology (race track design corridor)

The second set of impulse response measurements has taken place in a complex inter-connected corridor system with a race track layout design. This corridor is located in a different educational building from the 1960s era on the Georgia Institute of Technology campus. The total volume of the racetrack design corridor system is 895 m^3 (31,606ft^3). Its dimensional properties are as follows: height: 2.5m (8.2ft); width: 1.8-2.5 m (5.9ft-8.2ft) and total length: 173m (567ft). In total, this race track corridor includes 48 doors and 26 windows as shown in Figure 5.4.

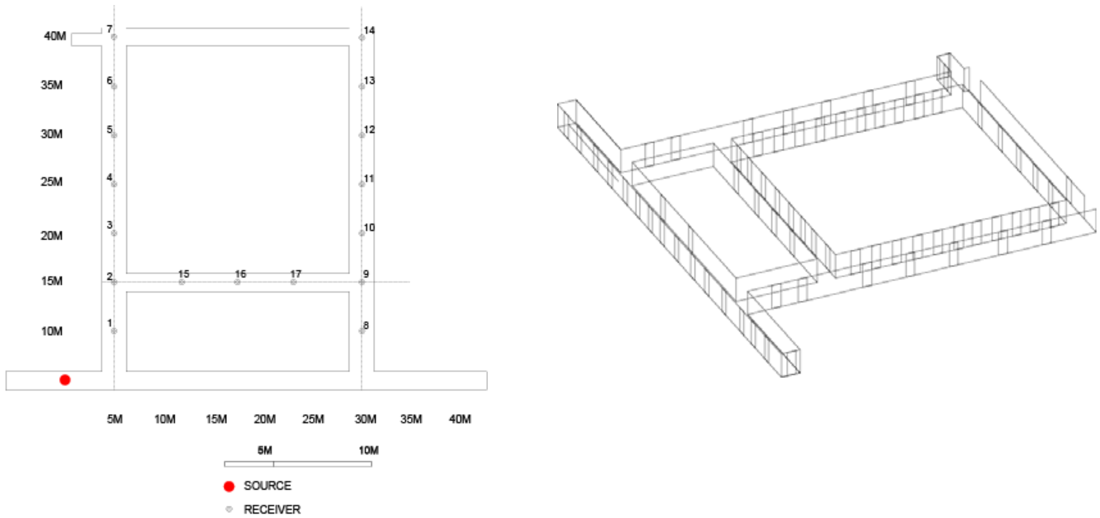


Figure 5.4 3D-CATT model and floor-plan of a race track corridor

The same space is modeled with the use of CATT-Acoustics simulation program. Similar materials are assigned to enclosure surfaces and receivers are located at identical locations. Table 5.4 shows the absorption coefficients of the materials assigned to surfaces of the acoustic model.

Table 5.4 Material absorption coefficients of the race track design corridor

Surface	Material	250Hz	500Hz	1kHz	2kHz	4kHz	SC
Door	Wood	0.21	0.1	0.08	0.06	0.06	A.E
Ceiling	Acoustic ceiling tile-(low absorption)	0.34	0.34	0.34	0.34	0.34	20%
	Acoustic ceiling tile-(medium absorption)	0.33	0.54	0.69	0.69	0.56	20%
Floor	Vinyl on concrete	0.03	0.03	0.03	0.03	0.02	10%
Window	Glass	0.25	0.18	0.12	0.07	0.04	A.E
Wall	Tile	0.01	0.01	0.01	0.02	0.02	30%

Findings (Race track design corridor)

The room-averaged predicted and measured reverberation time values across frequencies are shown in Figure 5.5. Similar to previous validation analysis, only sound behavior in the non-visual sound field is considered. JND for the room averaged reverberation times mostly range between 2% and 20% with a few exceptions (Table 5.5). Again based on the previous study findings, the difference between predicted and measured results is small enough to suggest the potential effectiveness of hybrid method in predicting reverberation qualities of race track design corridors.

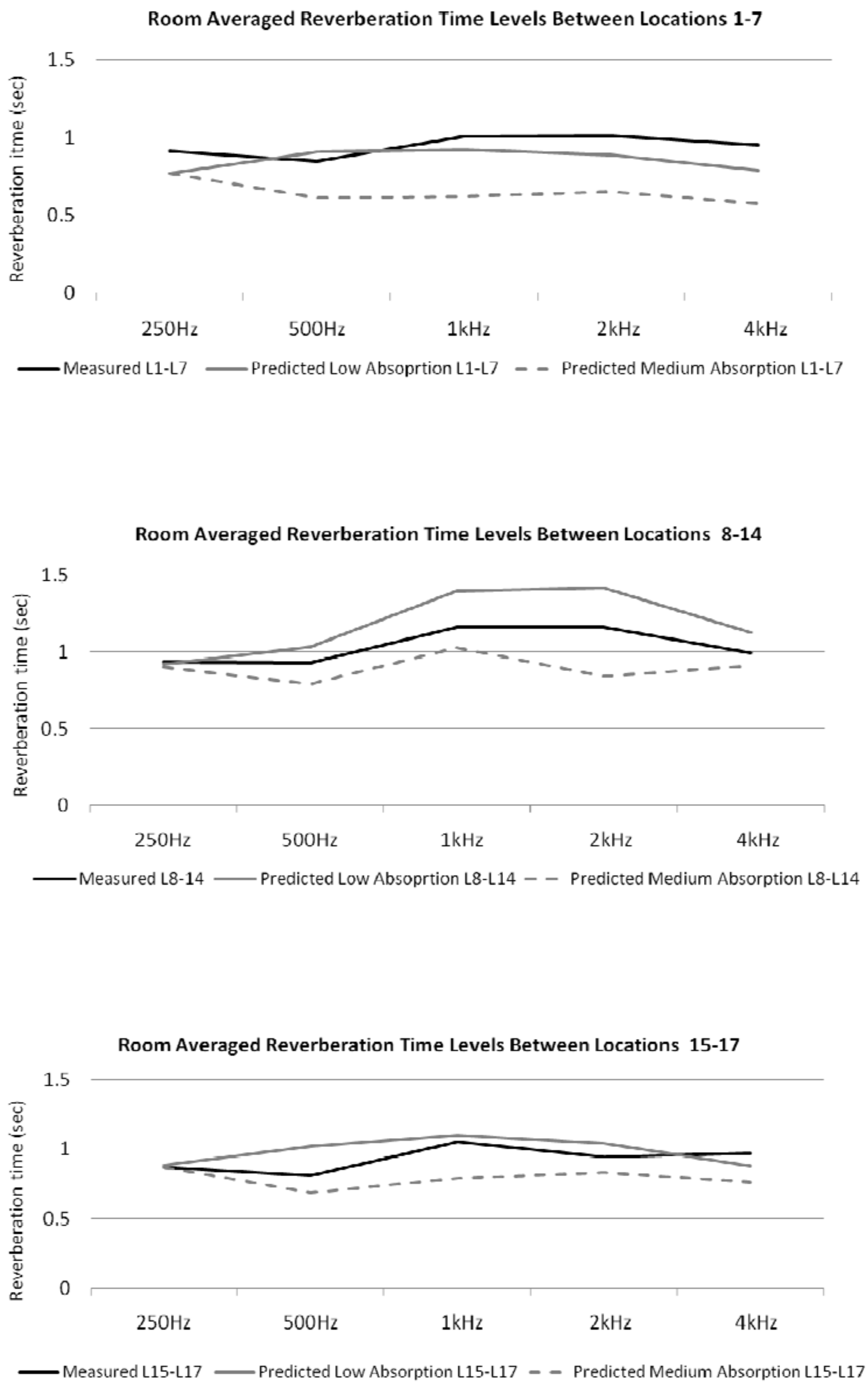


Figure 5.5 Room averaged measured vs. predicted reverberation times in a race track design corridor

Table 5.5 Just noticeable difference values for room averaged reverberation time (non-visual field)

JND (low abs)	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**
L1-7	15%	7%	8%	12%	17%
L8-14	14%	11%	20%	22%	14%
L15-17	2%	25%	5%	10%	9%

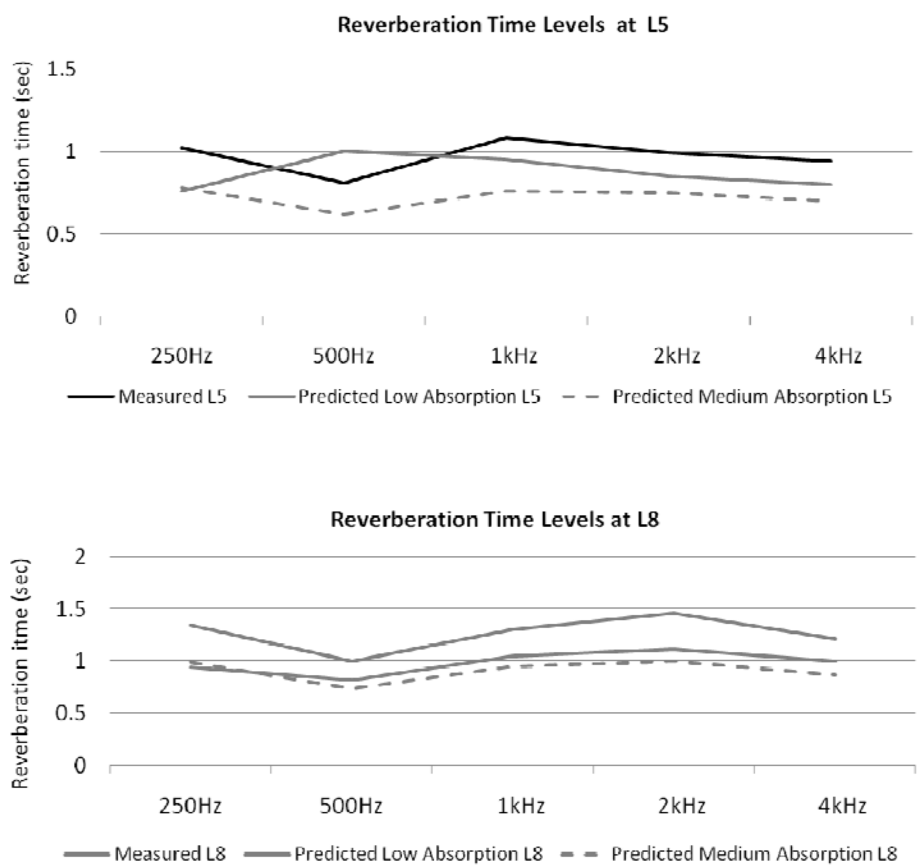
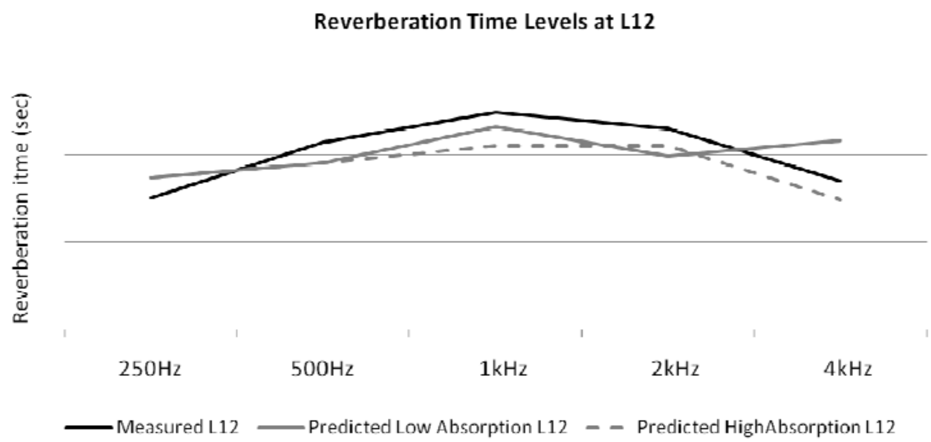


Figure 5.6 Measured vs. predicted reverberation times at the selected receiver locations in a race track design corridor

Figure 5.6 continued



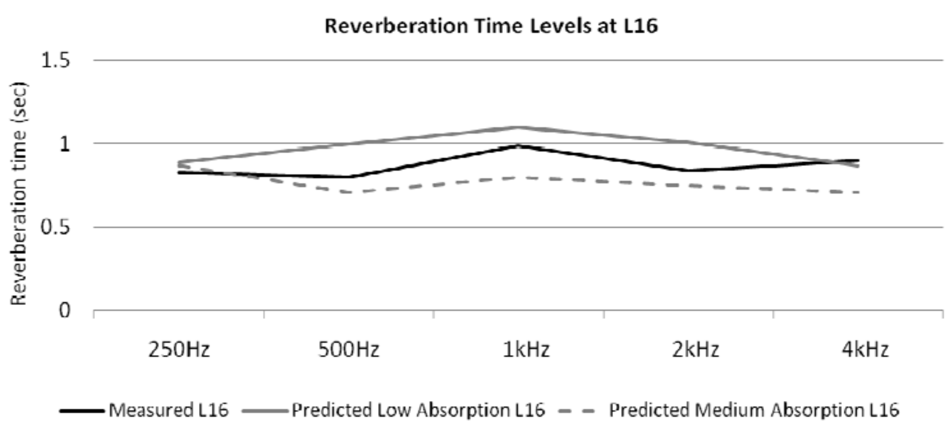


Table 5.6 Just noticeable difference values for reverberation times at the selected receiver locations (non-visual field)

JND (low abs)	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**
L5	22%	5%	3%	10%	16%
L8	5%	21%	22%	3%	20%
L12	16%	11%	6%	14%	24%
L16	7%	25%	11%	20%	3%

5.1.3 T-Shaped Corridor

Methodology (T-shaped corridor)

Third set of impulse response measurements took place in another complex inter-connected corridor system with a T-shaped layout design. This corridor is located in a different educational building from 1960s era on the Georgia Institute of Technology campus. The total volume of the corridor system with T-shaped floor-plated shape is 900m^3 (31,783ft^3). Its dimensional properties are as following: height: 2.4m (7.8ft); width: 2.3m (7.5ft) and total length: 111m (366ft). In total, the T-shaped corridor includes 33 doors and 19 small and 3 big windows from as shown in Figure 5.7.

The same space is modeled with the use of CATT-Acoustics simulation program. Similar materials are assigned to enclosure surfaces and receivers are located at identical locations. Table 5.7 shows the absorption coefficients of the materials assigned to surfaces of the acoustic model.

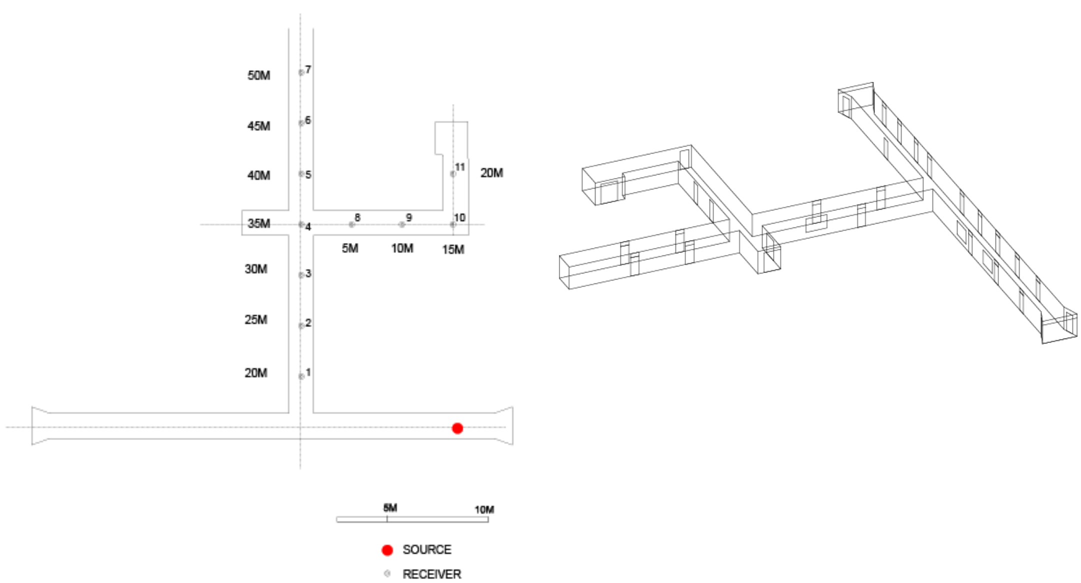


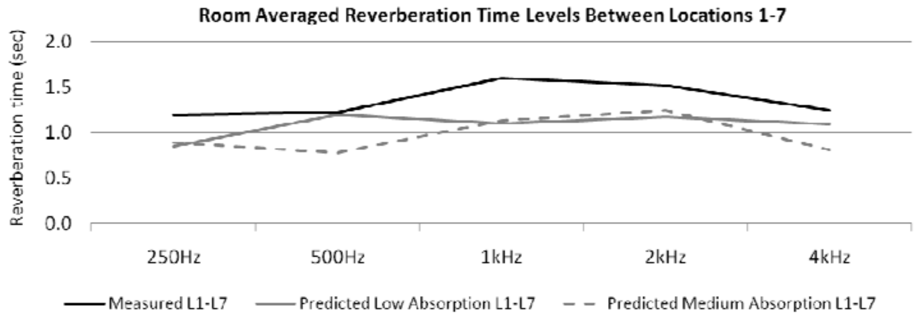
Figure 5.7 3D-CATT model and floor-plan of a T shaped corridor

Table 5.7 Material absorption coefficients of the T-shaped corridor

Surface	**Material**	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**	**SC**
Door	Wood	0.21	0.1	0.08	0.06	0.06	A.E
Ceiling	Acoustic ceiling tile (low absorption)	0.39	0.39	0.39	0.39	0.39	20%
	Acoustic ceiling tile- (medium absorption)	0.33	0.54	0.69	0.69	0.56	20%
Floor	Vinyl on concrete	0.03	0.03	0.03	0.03	0.02	10%
Window	Glass	0.25	0.18	0.12	0.07	0.04	A.E
Wall	Painted concrete	0.05	0.06	0.07	0.09	0.08	20%

Findings (T-shaped corridor)

Room averaged predicted and measured acoustic outcomes across frequencies are shown in the graphs below (Figure 5.8). JND values for room averaged RT30 levels range between 6% and 23% (Table 5.8). Figure 5.9 shows the measured and predicted RT30 levels at the selected receiver locations. JND values for RT30 levels at the selected receiver locations ranged between 3% and 24% (Table 5.9). Similar to the previous analysis, based on the previous study findings, the difference between predicted and measured results is small enough to suggest the potential effectiveness of hybrid method in predicting reverberation qualities of T-shaped corridors.



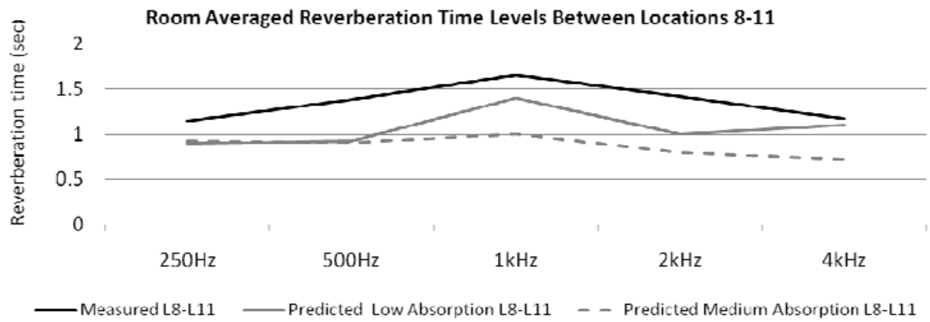
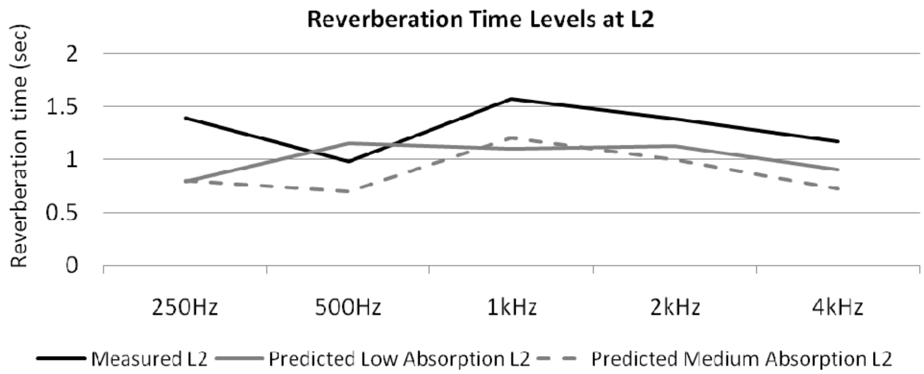


Figure 5.8 Room averaged measured vs. predicted reverberation times in a T-shaped corridor

Table 5.8 Just noticeable difference values for room averaged predicted and measured reverberation times (non-visual field).

JND (low abs)	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**
L1-7	22%	6%	23%	22%	12%
L8-11	21%	20%	15%	15%	6%



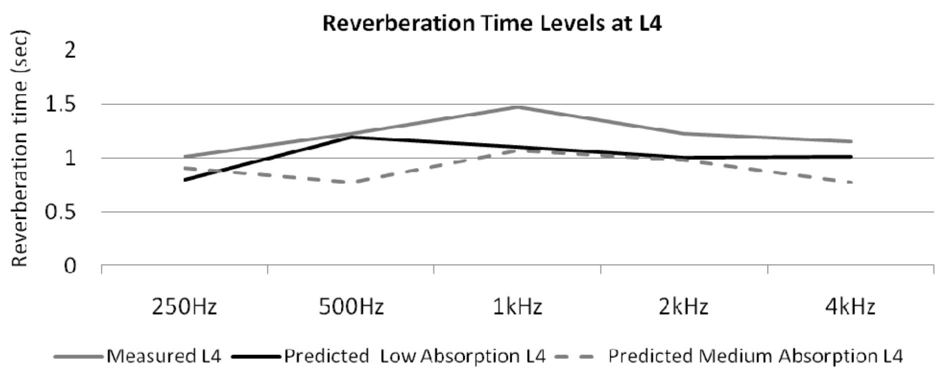
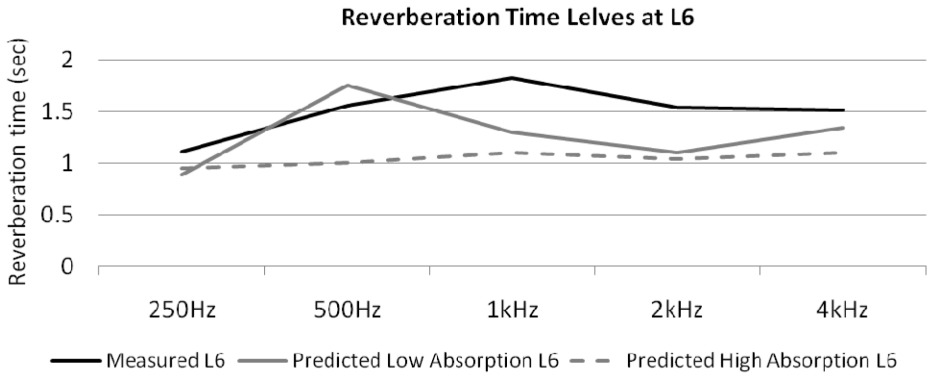


Figure 5.9 Measured vs. predicted reverberation times at the selected receiver locations in a T-shaped corridor

Figure 5.9 continued



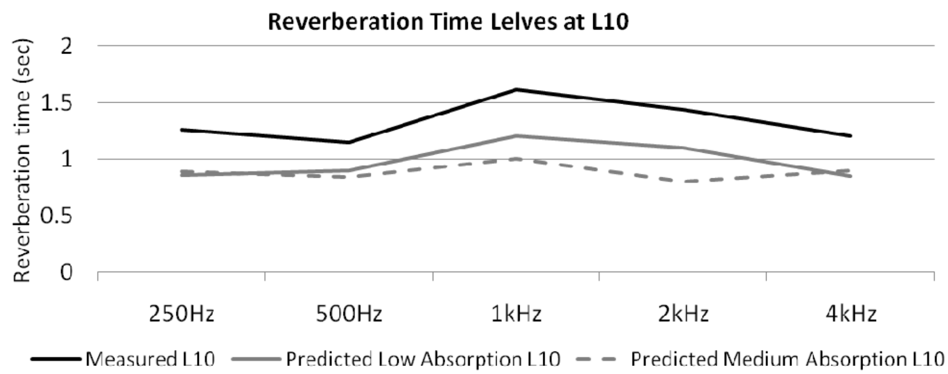


Table 5.9 Just noticeable difference values for reverberation times at the selected receiver locations (non-visual field)

JND (low abs)	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**
L2	15%	14%	20%	22%	23%
L4	12%	3%	22%	22%	14%
L6	24%	11%	21%	18%	13%
L10	20%	21%	19%	22%	22%

5.1.4 Conclusion

This part of the study has tested the effectiveness of CATT in estimating the acoustics of interconnected corridors. Related with the goals of this study, the measurements only have taken place in the non-visual sound field. Based on the jnd thresholds suggested by ISO 3382 standards, the differences between predicted and measured results are perceptible (i.e., 5% or greater). However, this is not a surprise when the findings of previous validation studies are considered. Typically the differences between measured and predicted RT30 results reported by other computer modeling studies are above the jnd thresholds suggested by ISO 3382. As the findings from this empirical study are parallel overall to the findings of previous research, this study suggests the potential effectiveness of hybrid method in predicting the room-averaged reverberation time outcomes for L-shaped, race track, and T-shaped corridors.

5.2 EMPIRICAL STUDY 2

SOUND BEHAVIOR IN SINGLE vs. INTERCONNECTED CORRIDORS

In addition to assessing the validity of an acoustic simulation tool in predicting acoustic qualities of long enclosures via Empirical Study 1, the other goal of this chapter is to understand the behavior of sound in long enclosures. Empirical Study 2 analyzes the differences between the diffuse sound fields of single and interconnected corridors via multiple impulse response measurements (in situ measurements) by conducting field measurements.

5.2.1 Methodology

Impulse response measurements have taken place in two different settings: a single corridor and a T-shaped corridor. Both settings are located in educational buildings on the Georgia Tech campus and had similar surface materials such as vinyl flooring, ceiling tiles, wood doors and concrete walls. Figure 5.10 shows the interior of the single corridor and Figure 5.11 shows the interior of the T-shaped corridor.

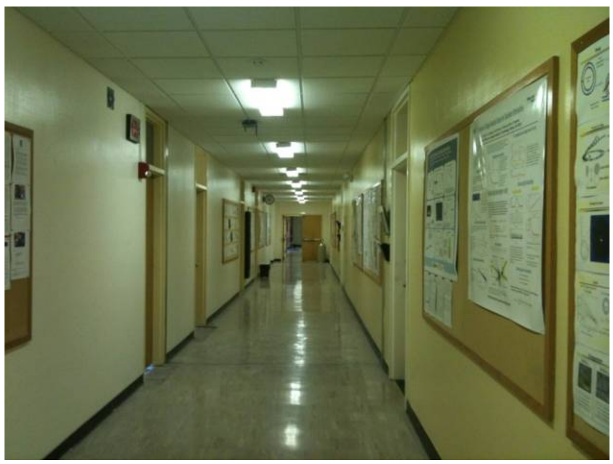


Figure 5.10 Interior of the single corridor setting

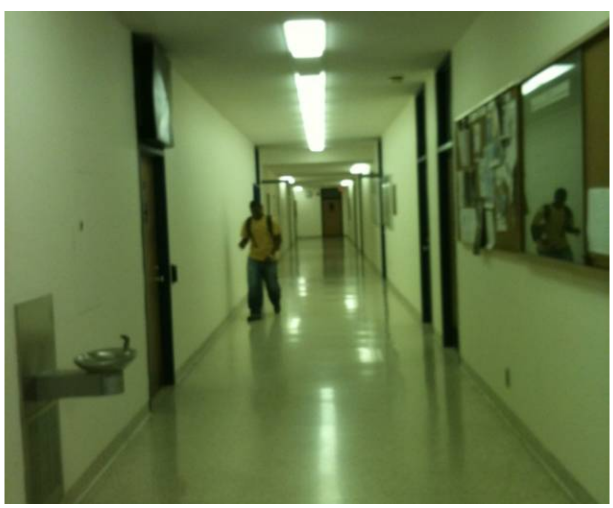


Figure 5.11 Interior of the T- shaped corridor

5.2.2 Findings

Figure 5.12 below shows the sound behavior in three corridor segments located in the two different corridor settings. The first corridor setting has a rectangular shape floor-plate. The second setting is an inter-connected corridor with T-shape floor-plate. As shown in the graphs included in Figure 5.12, reverberation times are not always the same at different locations of the two long enclosures. In the rectangular corridor, reverberation time values followed similar trends across frequency, where there is a trend for them to linearly increase with increasing distance from the sound source. However the sound behavior is more complex in the inter-connected hallways of the T-shape corridor. Thus, the behavior of sound in the non-visual-sound field (a.k.a. absence of direct sound) of the T-shaped corridor is more complex compared to the sound behavior in the visual-sound field (a.k.a. presence of direct sound).

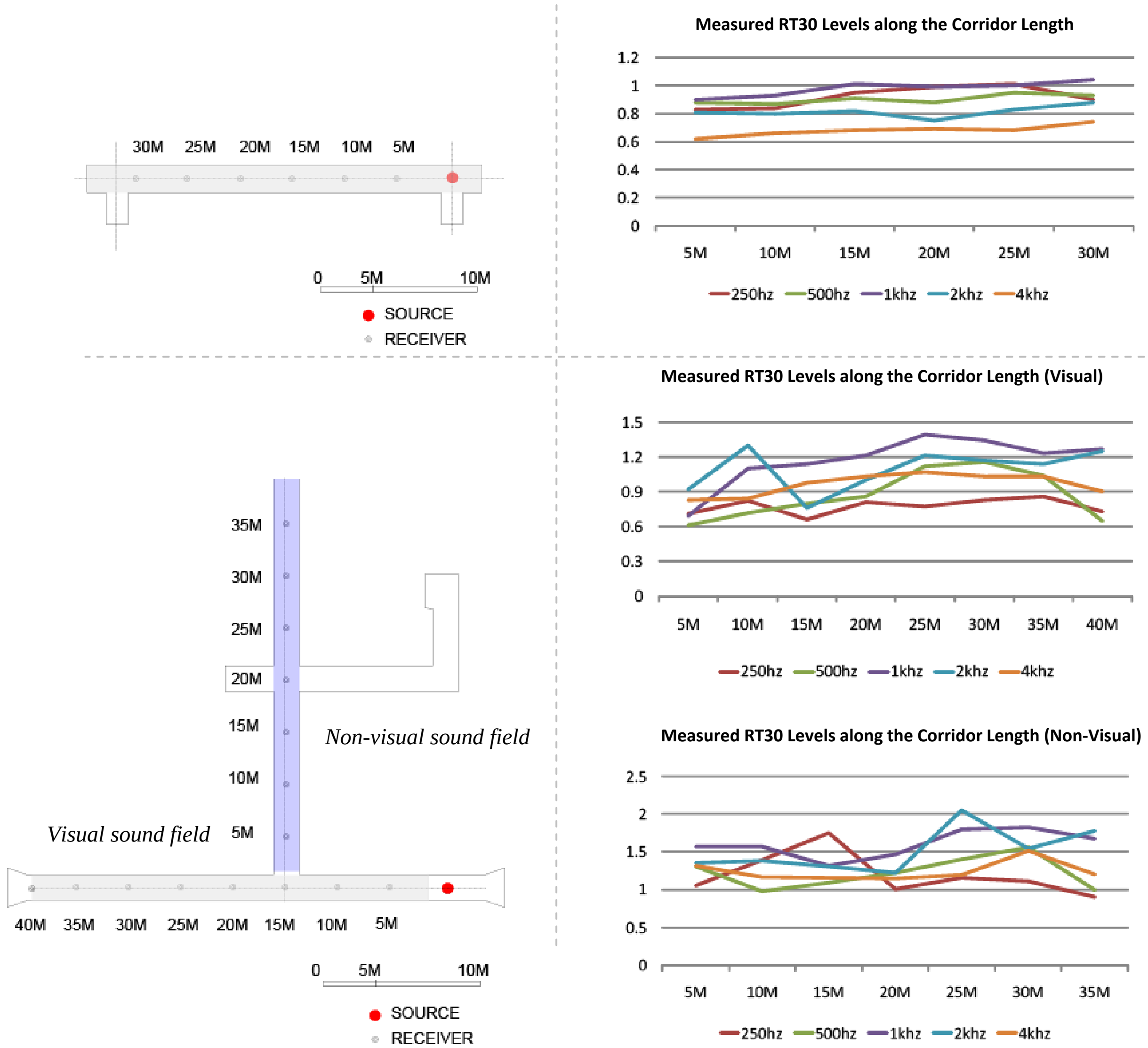


Figure 5.12 Measured reverberation times for the receivers located in the visual and non-visual fields of two different corridor settings with rectangle and T shaped-floor-plates

5.2.3 Conclusion

This study has conducted field measurements and acoustic simulations (1) to test the effectiveness of CATT in estimating the acoustic of interconnected corridors and (2) analyze the behavior of the sound in the single and inter-connected corridors.

In Empirical Study 1, usually the CATT- predicted results are within 5-22% accuracy, with a few exceptions. Even though predicted results are likely perceptibly different from the measured results, the agreement between them can still be considered acceptable based on the findings of the previous studies.

Overall, the findings of the validation studies conducted in this part of the study suggest the potential positive impact of CATT features such as hybrid prediction method, automatic edge function and diffuse reflections on the accuracy of the predicted RT30 outcomes particularly for the non-visual sound field of the long enclosures. Different from the visual sound field, in the non-visual sound field there is no direct visual connection between source and receiver.

In Empirical Study 2, the spatial distribution of reverberation times in the single and inter-connected corridors is similar to results reported by the previous research. In the single corridor, the trend of the data set is approximately linear for all frequencies. Similar to previous study findings, RT30 levels increases with increasing distance. This indicates the significant impact of distance on reverberation times particularly in the single corridors. Different from the single corridor case, the trend of the data sets recorded in the T-shaped corridor is not linear. In particular, the shape of the data set trend lines in the non-visual sound field of the T-shaped corridor is more complex compared to that in the visual sound field. This can be explained by the dominant effects of the reflections in the non-visual sound field. To further assess the impact of different design factors on reverberation time values in addition to distance, this study also conducts more controlled follow up studies The results are discussed in the following Chapters.

CHAPTER 6

DESIGN AND ACOUSTICS OF INTERCONNECTED HOSPITAL CORRIDORS

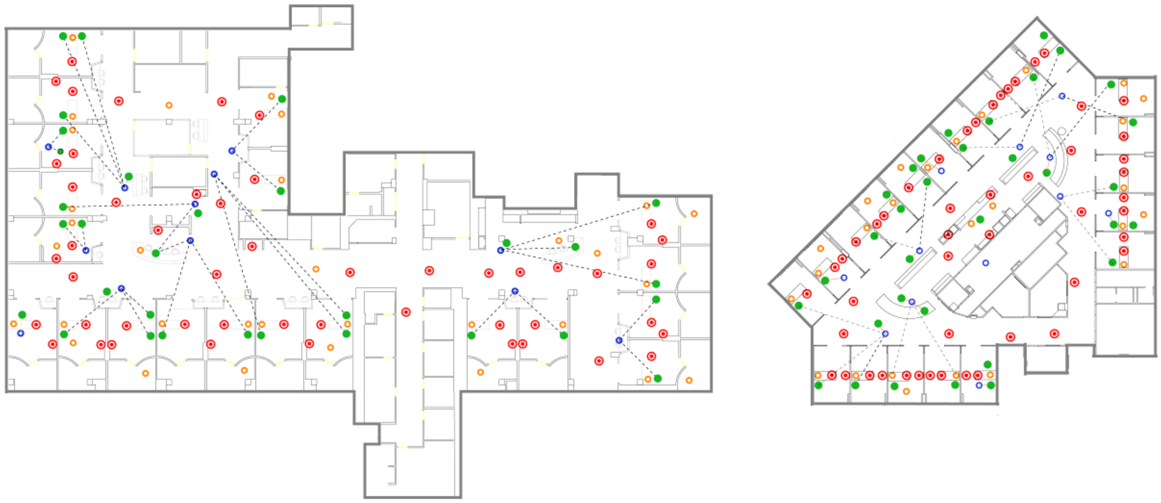
Field study findings conducted in the previous chapters indicate the potential significant impact of design features on the acoustic qualities of healthcare settings and highlight the necessity of conducting more controlled studies. Controlled studies can enable the analysis of the impact of particular design features on the acoustic qualities of healthcare settings while controlling for other interfering factors. Chapter 6 systematically explores the association between design and acoustics of interconnected nursing unit corridors with a focus on their reverberant qualities by conducting acoustic simulation analysis as well as in-situ impulse response measurements.

6.1 BACKGROUND

6.1.1 Auditory monitoring in the hospital corridors

Auditory patient monitoring is one of the key nurse tasks which might have life-death consequences. Preliminary study findings discussed in section 3.2.3 indicate that nurses monitor auditory cues at different locations including patient rooms, corridors, central and de-central nurse stations in the critical care units. In the patient rooms, assessment of auditory cues is supported with visual cues. Moreover, the nurses are very close to the sound source and receive direct sound which is one of the critical factors for effective auditory monitoring. However when they are mobile walking in the corridors, they most times do not receive direct sound. Therefore, conducting auditory monitoring in the corridors can be highly challenging.

Figure 6.1 shows the distribution of critical sounds, interfering noise sources, active (i.e., physician and nurse) and passive listeners (i.e., patient and visitors) in two ICUs. In these units one nurse is typically responsible for two patients in the unit. In these sound maps, lines are used to connect active listeners and the critical sound events that they monitor. Particularly in the ICUs and nursing units, caregivers are usually mobile in the corridors either dealing with other tasks or exchanging information with other caregivers. Moreover, in most hospitals, the local sound environments of nurse stations (central and de-central) are most times directly connected to the sound environments of corridors. Therefore, acoustic qualities of corridors also potentially affect the nurses` auditory monitoring performances at the nurse stations.



Red: noise sources
Yellow: Passive listener (i.e. patient and visitors)
Blue: Active listeners (i.e. caregivers)
Green: Critical sounds (i.e. medical alarms)

Figure 6.1 Spatial distribution of sound and noise source in the Neuro-ICU and MedSurg-ICU

6.1.2 Effects of reverberation time on auditory monitoring

Reverberant qualities of hospital sound environments can significantly affect perception of auditory cues. As described before, reverberation time represents the rate of the sound decay. Extended sound decay increases the length of reverberation time and masks the intelligibility of sounds including speech and non-speech sounds. For example, in a typical speech stream as the sound of a syllable decays, it tends to mask the sound of the subsequent syllable. The masking effects of two rooms with different reverberant qualities are shown in Figure 6.2. In the more reverberant room (RT30=2s) where the decay is slower, more sound is masked therefore speech intelligibility is lower. A hospital study also indicated the positive impact of reduced reverberation time values on speech intelligibility levels and improved psychosocial work environment reported by nurses (Hagerman et al., 2005).

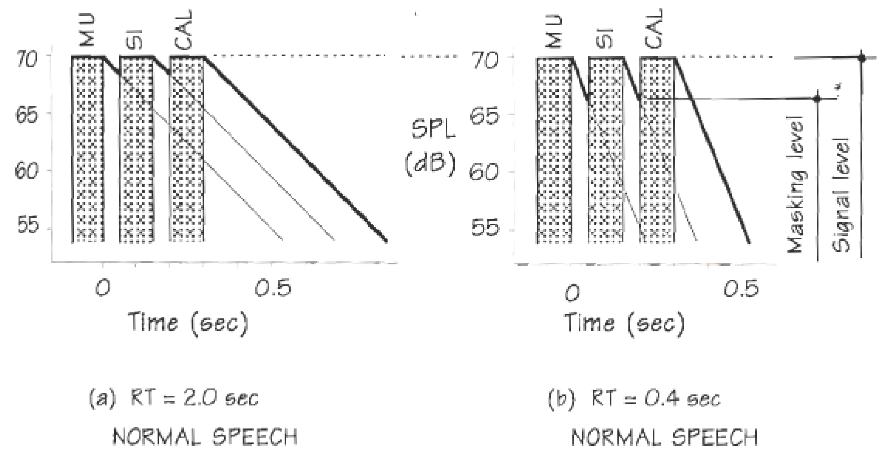


Figure 6.2 A speech sound that is masked differently in two rooms with different reverberation (from Mehta et al., 1997)

Reverberation time potentially impacts localization of auditory cues in hospitals. As described in Section 3.1.3, the human auditory system uses different cues when localizing sounds such as inter-aural differences in arrival time and intensity and spectral cues. However, late reflections caused by the boundary surfaces of rooms can result in dramatic physical changes to the sound waves such as sound energy and direction. “Late” reflections arrive later than the direct sound and early reflections. When late reflections dominate the direct sound and useful early reflections, and they negatively affect the sound localization (Litovsky, Colburn, Yost, & Guzman, 1999; Blauert, 1997). Therefore, the human auditory system mainly benefits from the first arriving energy when localizing sounds because it contains accurate localization information (Wallach et al., 1949). In cases where there is no direct sound such as in non-visual sound fields, the human auditory system depends only on the early arriving energy. Therefore, particularly in the non-visual sound field the impact of late reflections on sound localization can be highly detrimental.

Overall, high reverberation times can negatively affect sound tasks conducted by caregivers in the care settings. To assess task supportive design features of care settings, this research conducted more controlled studies and examined the association between different design features and reverberation time. The results of these studies are introduced in the following sections.

6.1.3 Design characteristics of hospital corridors

6.1.3.1 Scope

The architectural program of healthcare settings is composed of various functional spaces such as corridors, patient rooms, public and private visitor areas, staff work areas and lounges and medical care support areas. As discussed in Section 2, this study focuses on the design and acoustic characteristics of corridor settings. Caregivers spend a considerable amount of their time in the corridors while navigating between spaces. They also conduct critical sound tasks in the corridors including conducting critical medical conversations (e.g., patient care management, medication dosage and medical procedure) and localization and assessment of critical sounds. Poorly designed corridor settings can potentially aggravate the difficulty that caregivers experience while conducting critical sound tasks. In this part of the study, design characteristics of corridor settings located in 17 actual nursing units from hospitals located around the United States are analyzed.

6.1.3.2 Overall Corridor Design

Corridors in nursing units connect different types of spaces such as patient rooms, nurse stations and care support areas. As shown in Figure 6.3, the total length of the corridors connecting different spaces in the entire nursing unit range between 87m (285ft) and 467m (1,532ft). Additionally, a nursing unit can consist of different numbers of connected hallways forming complex floor-plate shapes as shown in Figure 6.4. The nursing unit in Paimio Hospital and Bellevue Hospital consist of two intersecting hallways. In the rest of the nursing units, the number of hallways ranged between 3 and 17.

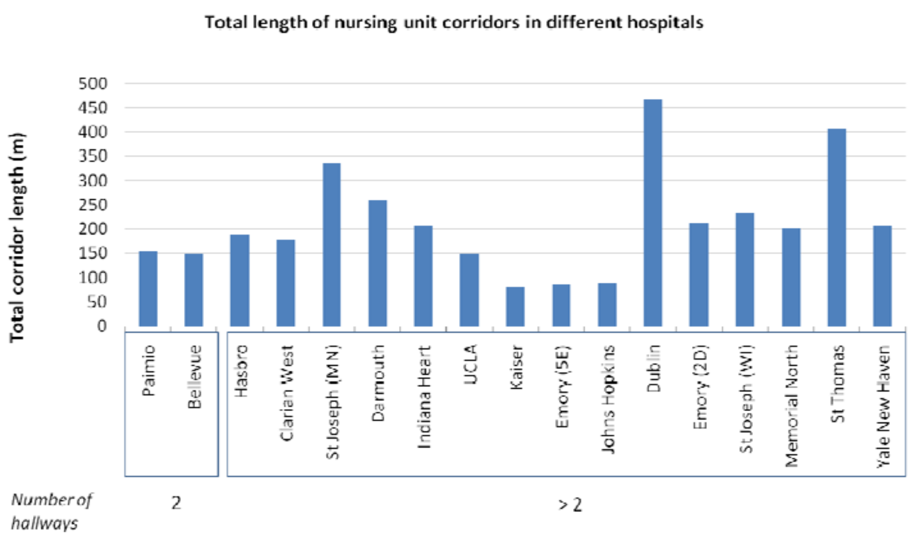


Figure 6.3 Total length of the nursing unit corridors in different hospitals, expressed as number of hallways

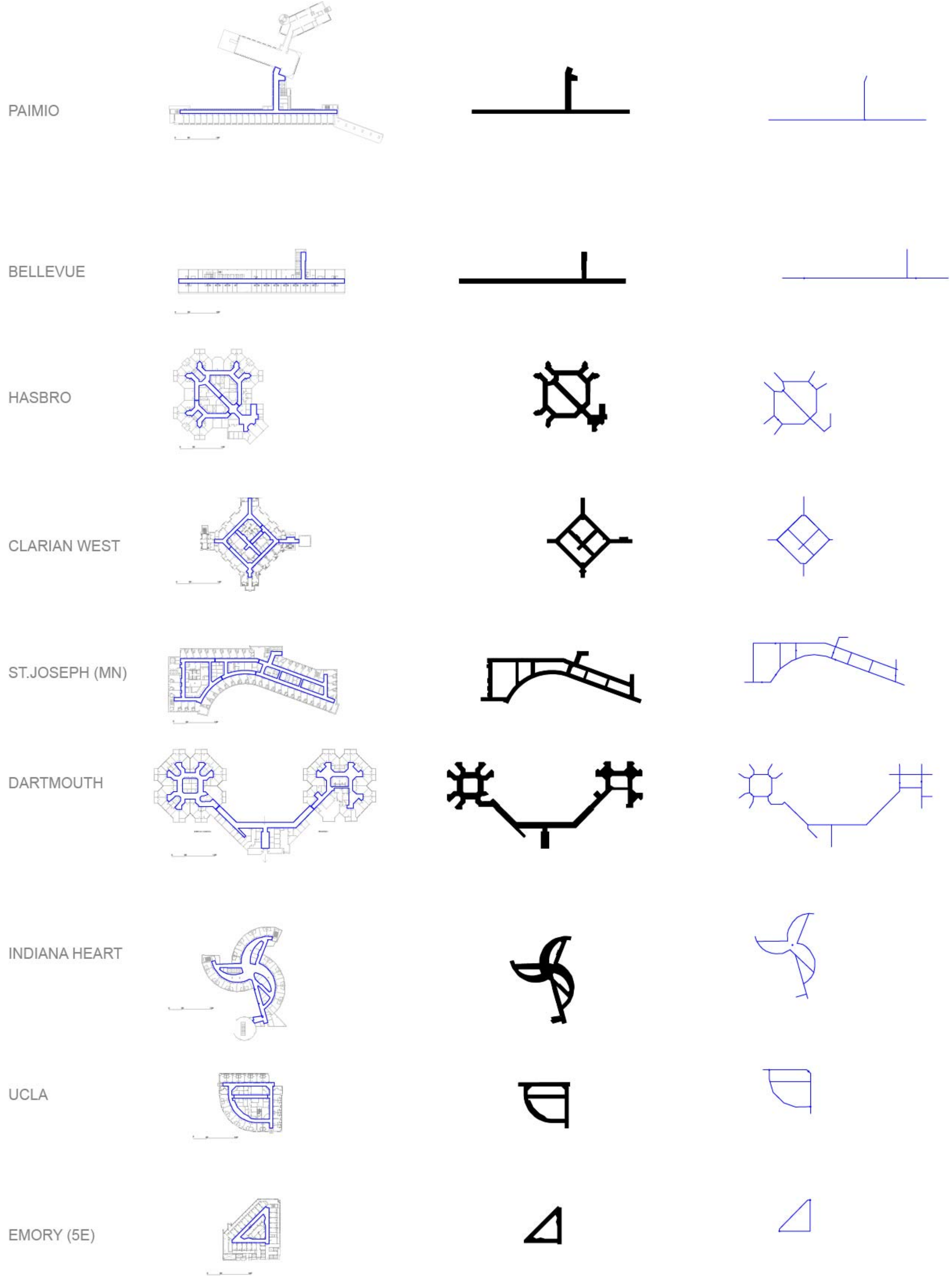
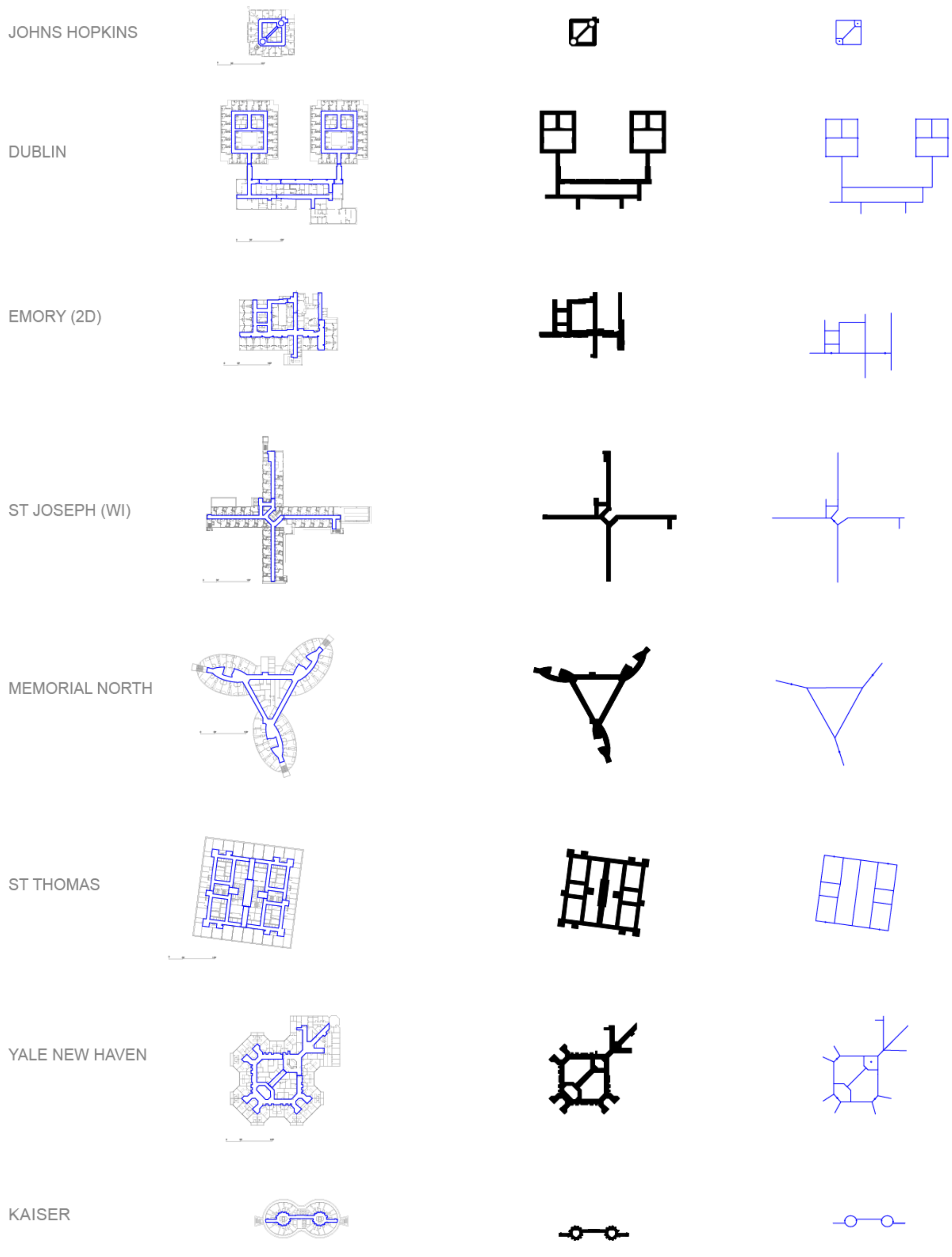


Figure 6.4 Floor plans of nursing units located in different hospitals (Floor-plans of the hospitals were collected by a group of PhD students including myself as a part of the Hospital Typology Class led by Dr John Peponis, Dr Sonit Bafna and Dr Craig Zimring)- *All drawings are in the same scale*

Figure 6.4 (continued)



Except for the nursing units of Paimio Hospital and Bellevue Hospital, all nursing units shown in Figure 6.4 consist of multiple patient-care clusters. Related with care management and infection control purposes, typically patient-care clusters and their corridors are segregated from other patient-care clusters with operable doors. The result is that each patient-care cluster operates as a unique sound environment. This study conducted another design analysis to assess floor-plate design characteristics of nursing unit patient-care cluster corridors segregated with doors. A total of 43 different types of clustered corridors were reviewed (Figure 6.5).

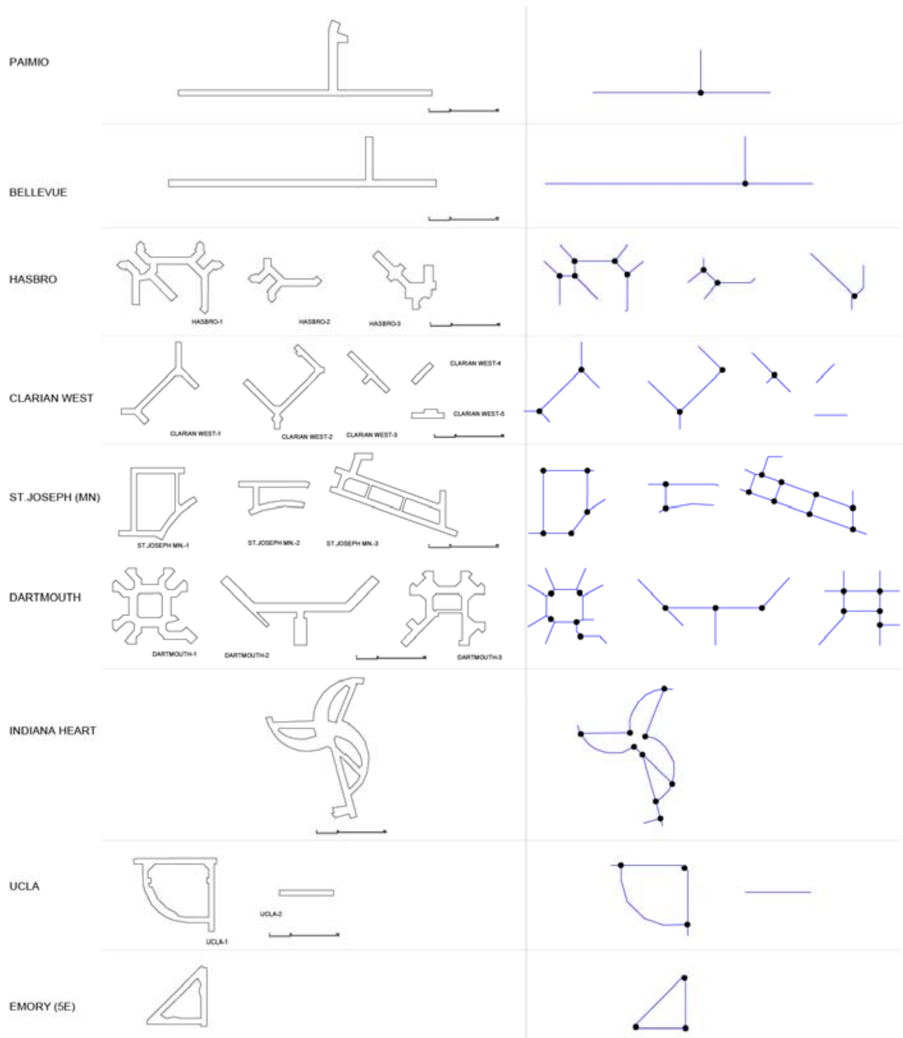
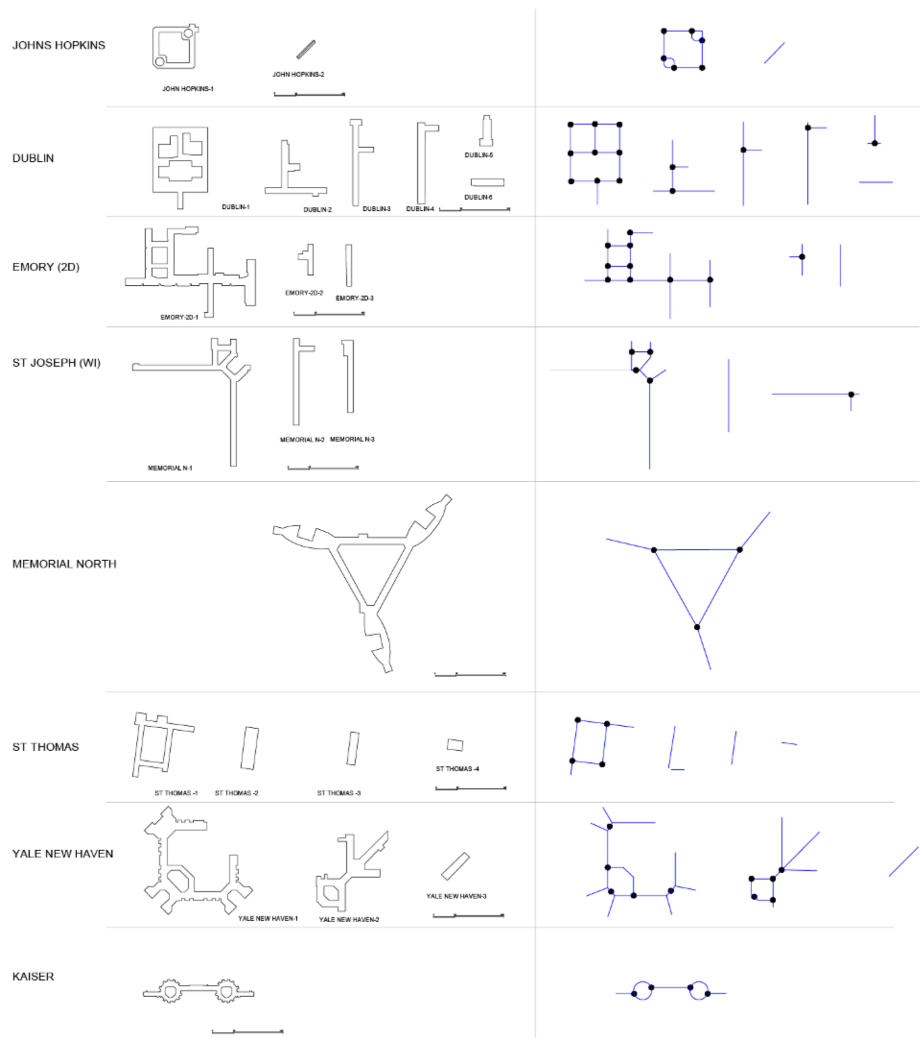


Figure 6.5 Floor plans of clustered corridors

Figure 6.5 (continued)



The number of segregated patient-care corridors with different floor-plate shapes varies among different nursing units and ranges between 1 and 6 as shown in Figure 6.6.

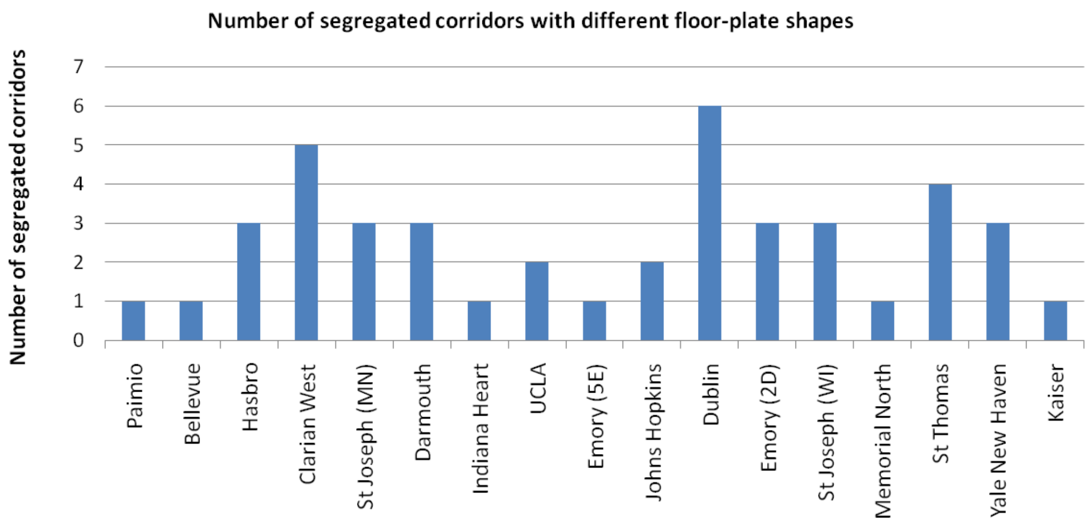


Figure 6.6 Number of clustered corridors in the nursing units

6.1.3.3 Corridor Spatial Organization

Spatial organization of spaces on the nursing unit layouts has been classified in different categories by James and Tatton-Brown (1986) based on the examination of more than 60 hospital designs (Figure 6.7). These layout design categories are nightingale, corridor or continental, duplex or Nuffield, racetrack or double corridor, courtyard, cruciform or cluster and radial type. The logic behind the formation of these layout configurations is outside the scope of this study. However it needs to be noted that each of these layout types differently contribute to visual patient monitoring based on different organizations of nurse stations around clusters of patient rooms. Detailed information about these layouts can be obtained from the following sources: James and Tatton-Brown (1986); Rashid (2006).

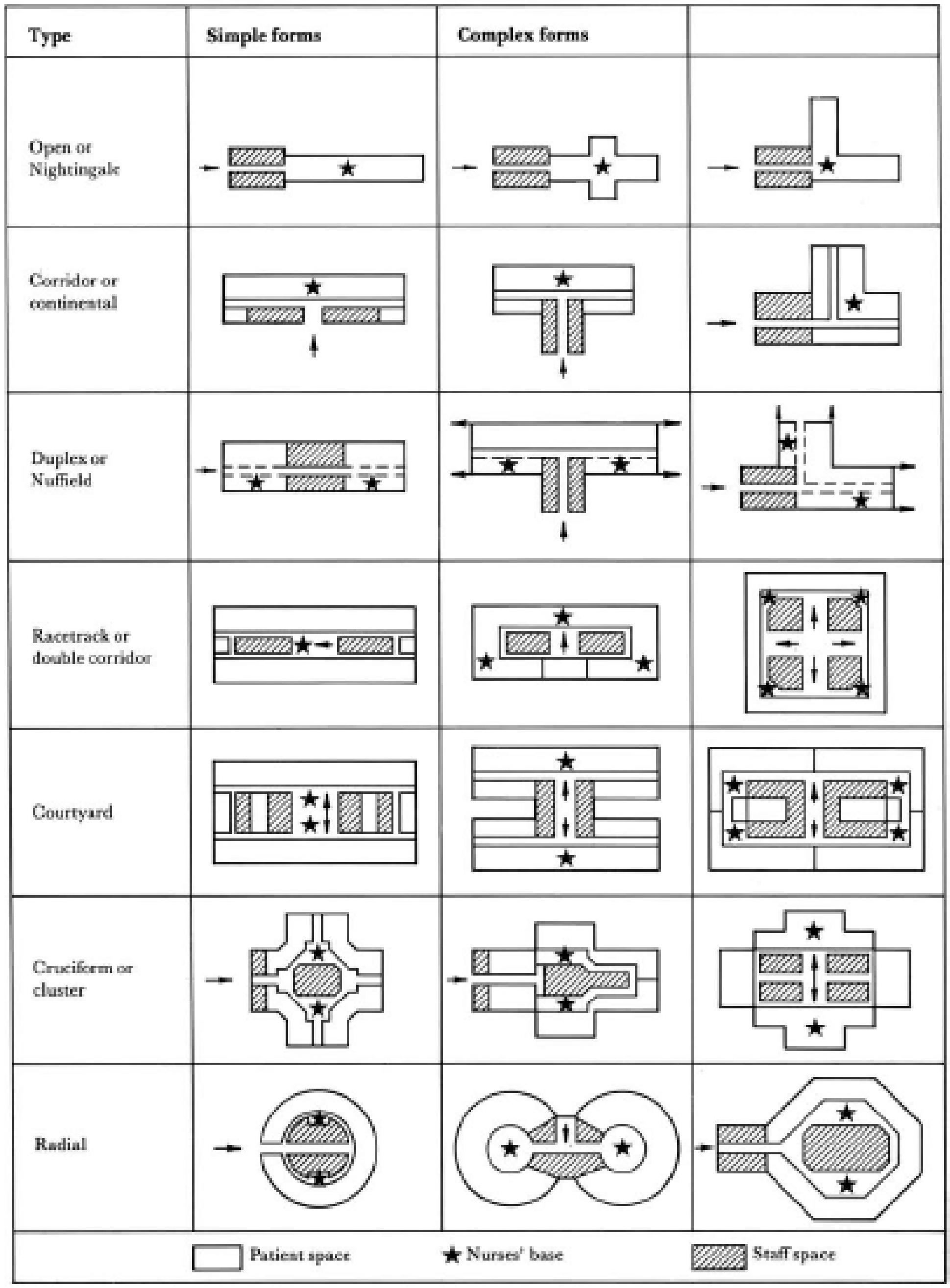


Figure 6.7 Nursing unit layout types (from James, & Tatton-Brown, 1986)

Based on their influence on sound propagation, the floor-plate shapes of the 44 different clustered corridors shown in Figure 6.5 can be grouped in two categories: race track design and tree-like design. In a race track design, corridors surround the centralized care support areas and make a loop around those care support areas. On the other hand a tree-like design includes straight, segmented or intersecting corridors. As shown in Figure 6.8, in a race track design corridor setting sound propagates in two major directions away from a source. On the other hand in a tree-like design corridor, sound propagates in one major direction.

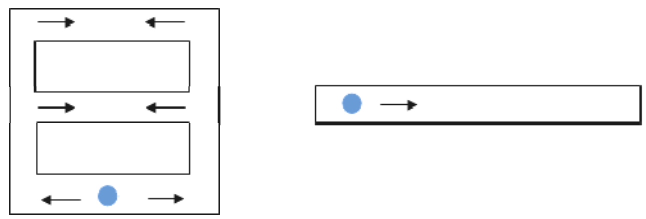


Figure 6.8 Sound propagation in race track and tree-like design corridors (a) Race track design hallways (b) tree-like design corridor (Blue dot represents the sound source and arrows represent the sound rays)

Tree-like design corridors can have a variety of different floor-plate shapes including I, T, L, cross and different combinations of I, L and T. Race track design corridors can also have various floor-plate shapes including rectangular, triangular and circular floor-plate shapes. However, race track design with rectangular floor-plate shapes is the most common. Moreover, in many cases parallel hallways in these rectangular floor-plates are connected with intersecting sub-hallways. The distance of these sub-hallways to parallel main hallways ranges between 10m (33ft) and 24m (79ft).

Overall, the width of the corridors (including both tree-like design and race track design) varies between 2m (6.5ft) to 4.7m (15.4ft) while usually it is approximately 2.7m (8.8ft). The total length of the corridors composed of one hallway ranges between 8m (26ft) and

34m (111ft) as shown in Figure 6.9. However, usually the corridor clusters are composed of multiple hallways. The total length of the corridor clusters with multiple hallways ranges between 30m (98ft) and 210m (689ft). Except Bellevue and Paimio, the length of each individual hallway composing these corridor clusters mostly ranges between 15m (49ft) and 40m (131ft).

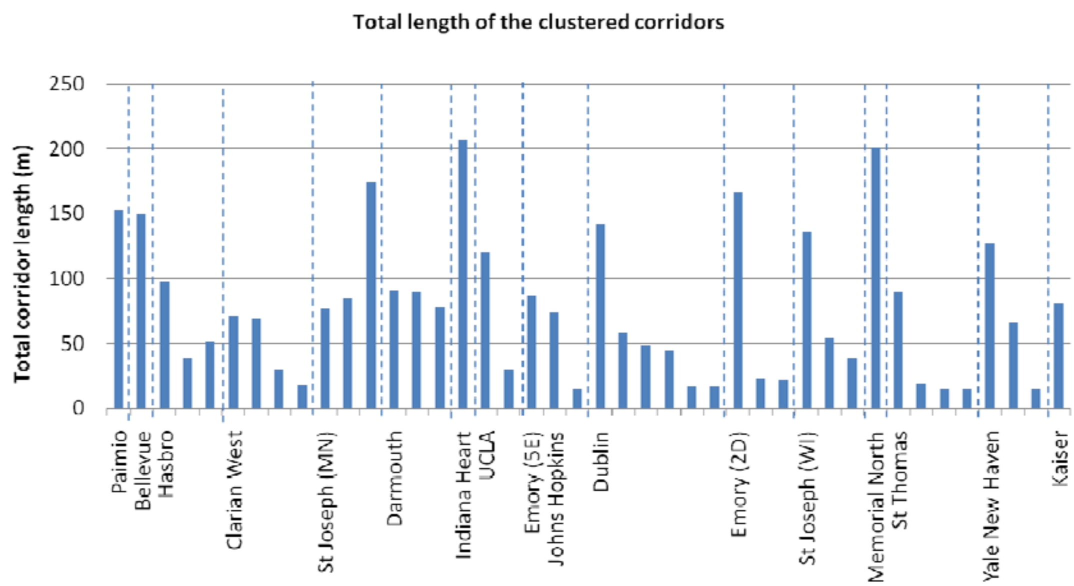


Figure 6.9 Total corridor length of corridor clusters

6.2 PILOT STUDY

LINKING ACOUSTICS AND DESIGN VARIABLES OF ACTUAL EDUCATIONAL CORRIDORS

6.2.1 Scope

In sufficiently diffuse sound fields, reverberation time is primarily a function of two room parameters: room volume and absorption. In non-diffuse sound fields such as long enclosures, there are different design factors that have been found to have impact on reverberation time values such as size and shape of the cross section, distribution of absorptive materials on boundary surfaces and reflective qualities of surface materials (diffuse vs. geometrical). However, the impact of floor-plate design of corridors on reverberation time has not yet been systematically investigated. To statistically assess the association between floor-plate design variables and reverberant qualities of corridor sound environments, a pilot study is conducted in the inter-connected corridors of the actual educational settings. The other goal of this pilot study is to provide input for the more controlled acoustic simulation studies that follow. In this pilot study, design characteristics of particular hallways composing inter-connected corridor systems are correlated with the reverberant qualities of the sound environments.

6.2.2 Methodology

Field measurements have taken place in 5 corridor settings located in 3 different educational buildings on the campus of Georgia Institute of Technology. The floor-plate shapes of these interconnected corridors are shown in Figure 6.10. Each inter-connected corridor is composed of several hallways and the length of the hallways ranged between

15m (49ft) to 45m (148ft). The red dot placed in the corridor drawings is used to represent sound source locations and lines are used to illustrate the paths where receivers are systematically distributed 5m (16ft) apart from each other. Color code is applied to represent the receivers located at different hallways that are 1 and 2 turns away from the sound source.

Design characteristics of each single hallway represented with an ID number in Figure 6.10 are correlated with mean and standard deviation of reverberation time values measured in the same hallway. Some of the design variables considered in this analysis include corridor length, number of branches (number of connected corridors to a single corridor), number of turns and radial distance from the source. The effects of these design variables on reverberation time values are assessed while controlling for other design factors such as material and volume. The acoustic measure considered in the analysis is mean reverberation time values. Mean values (represented as "RT-Mean" in Table 6.1) represent the overall/averaged reverberation time values in each hallway. The mid frequency range (500Hz and 1 kHz) is considered in particular because of its significant importance for human hearing perception.

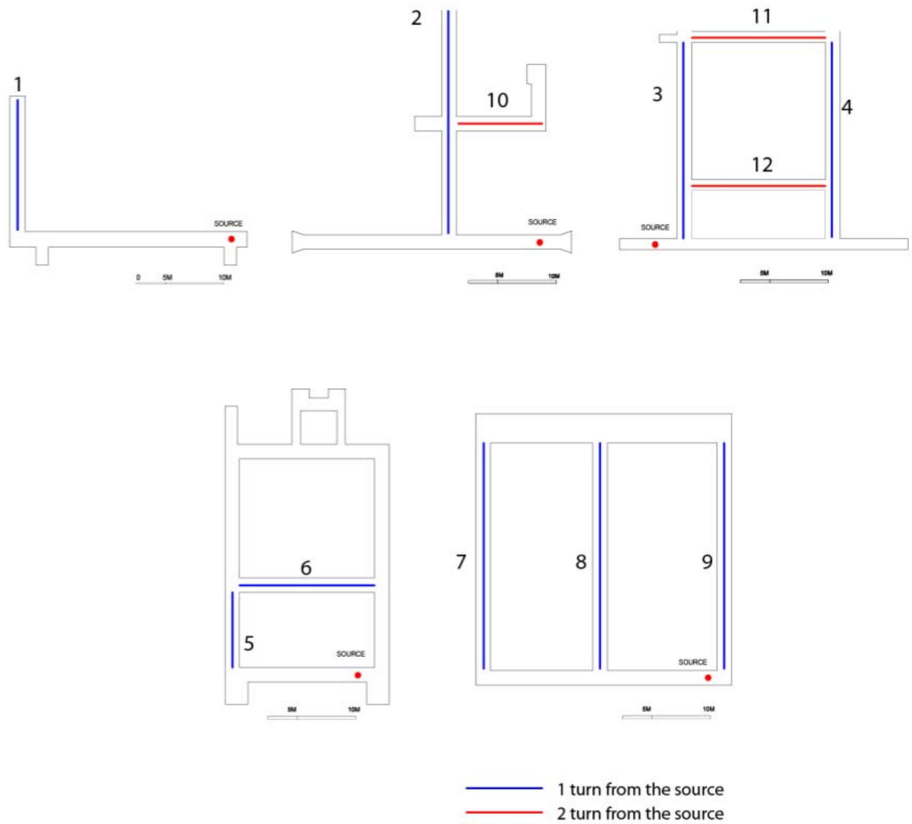


Figure 6.10 Plans of the corridors located in the educational buildings where impulse response measurements were conducted

In this study, the design variable "number of turns" represents the order of the visibility zones from the sound source location. For example the hallway/zone visible from the sound source location is considered as "0-order visibility zone" and the hallway/zone perpendicularly connected to the 0-order visibility zone is considered as "1st order visibility zone". Similarly, the hallway/zone perpendicularly connected to this 1st order visibility zone is considered as "2nd order visibility zone". The zone visible from the sound source is referred as "visual field" in the following sections of this work. Receivers located in the hallways where they do not have any visual connection with the sound source (a.k.a. lack of direct sound energy) referred as the "non-visual sound field" are found to experience longer reverberation times. The “critical distance” in all educational corridor settings ranges between 5m (16.4ft) and 15m (49ft). Critical distance is the distance where both the energy of the direct and reflected sound is equal. Conducting acoustic measurements outside the critical distance is important to avoid the effects of direct sound on acoustic outcomes. In this research, all impulse response measurements are conducted outside the critical distance.

6.2.3 Findings

Partial correlation analysis results presented in Table 6.1 indicate that when other interfering design variables are controlled (total volume, average distance, corridor length, number of branches and material), the *number of turns* design variable is significantly and positively correlated with mean reverberation time values. In other words, receivers located at the hallways where they have a visual connection with the sound source (a.k.a. presence of direct sound energy) are found to experience lower reverberation times. Compared to receivers located in the non-visual zones with lower visibility order, receivers located in the non-visual zones with higher visibility order are also found to experience longer reverberation time. It needs to be noted that these interpretations are limited to 1 and 2 turns because of the characteristics of the hallways included in the sample group.

Table 6.1 Partial correlation analysis results linking corridor design variables, mean of reverberation times (RT-Mean) and standard deviation of reverberation times (RT-SD)

Independent corridor design variable	**Control Variables**	**Frequency**	**RT-Mean Partial correlation coefficient**
Corridor length	Number of branches Number of turns Material Avg. distance Volume	500Hz	0.60**
		1kHz	0.50**
Number of branches	Corridor length Number of turns Material Avg. distance Volume	500Hz	- 0.35
		1kHz	- 0.30
Number of turns	Corridor length Number of branches Material Avg. distance Volume	500Hz	0.60**
		1kHz	0.70**

* When controlled for the other variables, the correlation b/w variables is statistically significant at 0.1 level (p<0.1)
** When controlled for the other variables, the correlation b/w variables is statistically significant at 0.05 level (p<0.05)

The design variable *number of branches* is used to represent the number of hallways connected to a single hallway. According to partial correlation analysis, when other interfering design variables are controlled (total volume, average distance, corridor length, number of turns and material), the *number of branches* design variable is negatively but not significantly correlated with mean reverberation time. In other words, this finding suggests that in the hallways with higher number of branches, reverberation time values are expected to be lower. The impact of corridor length on reverberation time values is also investigated with partial correlation analysis. The length of the corridors is found to be significantly and positively correlated with mean reverberation time values when other interfering design variables were controlled (total volume, average distance, number of turns, number of branches and material). This finding suggests that as the length of a particular hallway increases, overall (averaged) reverberation time value in the particular hallway are also expected to increase. The results of this analysis also agreed with the earlier sound behavior analysis results. As shown in Figure 5.12, reverberation time tends to increase with increasing hallway length.

Another partial correlation analysis is conducted to assess the impact of radial distance on reverberation time values. This analysis is partially different from the others because the mean reverberation time values are not used this time. Instead, reverberation time values measured at each receiver location are directly correlated with *radial distance* (direct distance instead of walking distance) between the sound source and the receiver location. As shown in Table 6.2, when volume and material are controlled for, *radial distance* is found to be significantly and positively correlated with reverberation time at discrete distances. This finding suggests that receivers located at positions with longer radial distance from the sound source are expected to experience longer reverberation time values compared to receivers located at positions with shorter radial distance.

Table 6.2 Partial correlation analysis results between corridor design variables of radial distance and reverberation time at discrete distances.

Independent corridor design variable	**Control Variables**	**Frequency**	**RT at discrete distances Partial correlation coefficient**
Radial distance	Material Volume	500Hz	0.56**
		1kHz	0.50*

* When controlled for the other variables, the correlation b/w variables is statistically significant at 0.1 level (p<0.1)
** When controlled for the other variables, the correlation b/w variables is statistically significant at 0.05 level (p<0.05)

Overall, the findings of the pilot study analysis indicate the potential effects of floor-plate design features on the acoustic qualities of corridor sound environments. In the following sections, these findings are followed up with more detailed and controlled simulation studies.

6.3 EMPIRICAL STUDY 1

LINKING ACOUSTICS AND DESIGN VARIABLES OF 60 THEORETICAL CORRIDOR MODELS

6.3.1 Scope

The pilot study introduced in previous section has statistically investigated the relationship between reverberation time and design variables of real life corridors with complex floor-plate shapes. Some of these design features such as number of turns and corridor length are found to be significantly associated with mean reverberation time values. These interpretations are based on field measurements conducted in the actual settings. In this part of the study, a more controlled follow up study is conducted to enable the systematic analysis of the relationship between design and acoustic characteristics of hallways located only in the non-visual sound fields of corridors with complex floor-plate shapes. The motivation for focusing on non-visual sound fields is to control for the interfering effects of direct sound present in the visual-sound field on acoustic outcomes.

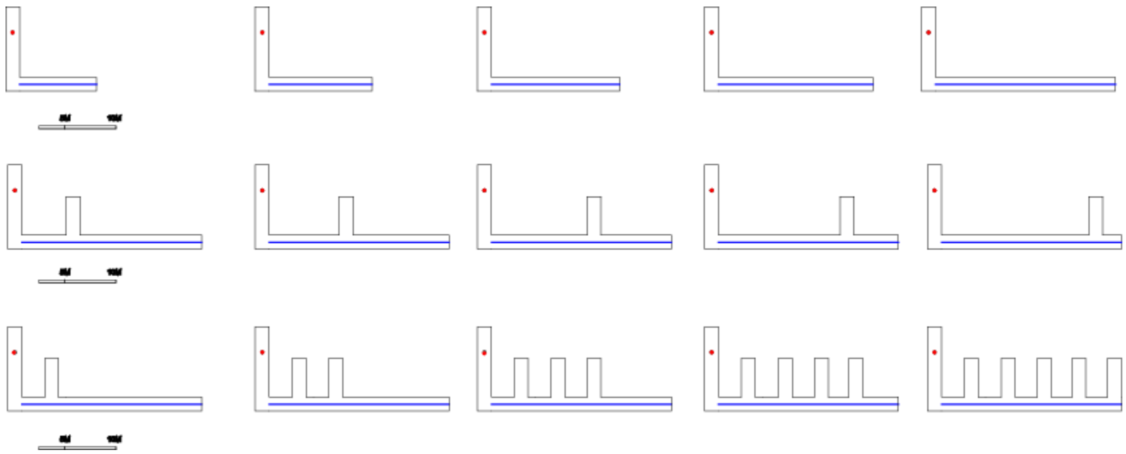
6.3.2 Methodology

Based on the heuristic analysis findings described in Section 4.2.1, 60 different theoretical models are generated as shown in Figure 6.11. The total lengths of the corridors composed of multiple hallways range between 30m (98ft) to 215m (705ft). The length of each individual hallway included in these theoretical models range between 15m (49ft) and 40m (131ft). Among all theoretical models, corridor width (3m/9.8ft) and height (3m/9.8ft) are the same.

Several layers of grouping are used to group the 60 theoretical models to control for the effects of interfering design factors, as shown in Figure 6.11. The theoretical models are first grouped based on their layout design types: tree-like design and race track design. For each layout design type, 30 different theoretical models are generated. Theoretical models in each group are further grouped based on *number of turns*. In addition to layout design type, controlling for *number of turns* is necessary because Phase 1 pilot study findings have indicated the significant association between this corridor design variable and reverberation time values. The red dots in Figure 6.11 represent a theoretical sound source. The hallways of the theoretical models that are 1 turn and 2 turns away from the sound source are highlighted with blue and red lines respectively. In total, 15 different theoretical models are generated for each *number of turns* category. Those models are further grouped under three categories to allow systematic study of different design variables including *branch number, branch distance and corridor length*.

Acoustic qualities of these models are analyzed with CATT acoustic simulation program. The sound source is located 5m (16ft) away from one of the end walls. Multiple receivers are located 5m (16ft) apart from each other along the hallways highlighted with red or blue lines. Two different acoustic analyses are conducted to assess the impact of two levels of absorption on the association between the design and acoustic variables. At first, all surfaces are assigned a material with 0.1 absorption coefficient (α). Second, all surfaces are assigned a material with $\alpha = 0.3$. These particular absorption coefficients are chosen because they represent *room averaged absorption coefficients* of hospital settings installed with lower and higher performance acoustic ceiling tiles. In total, 120 different acoustic simulation analyses are conducted.

Test cases #1: tree-like design | 1 turn



Test cases #2: tree-like design | 2 turns

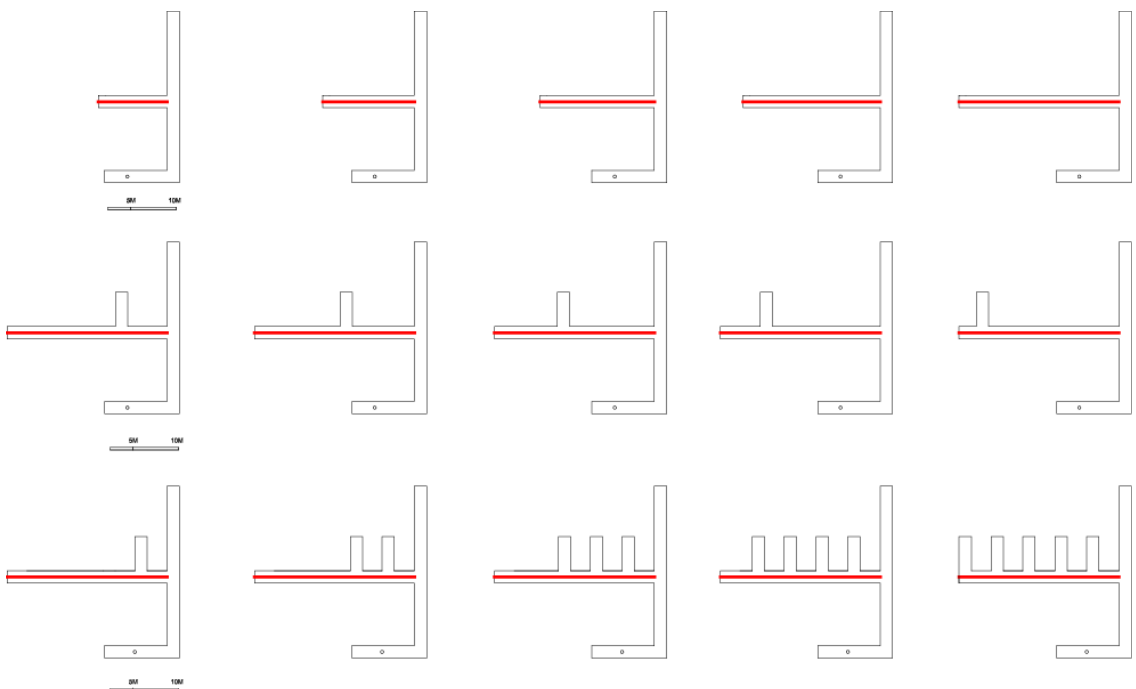
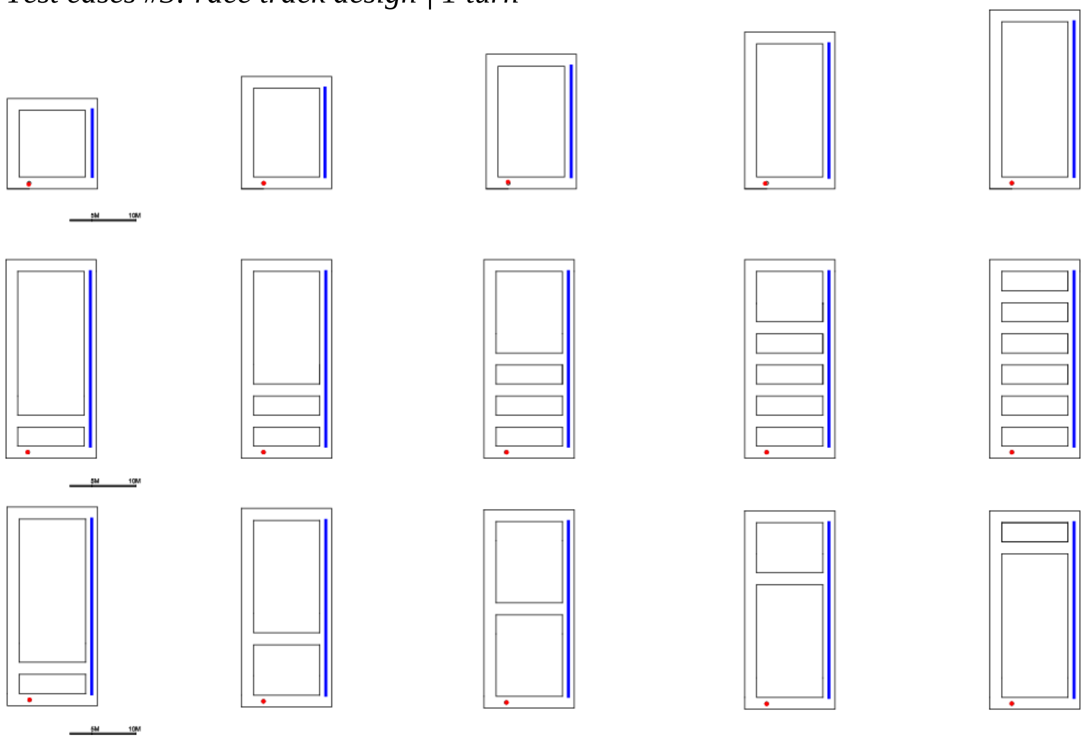


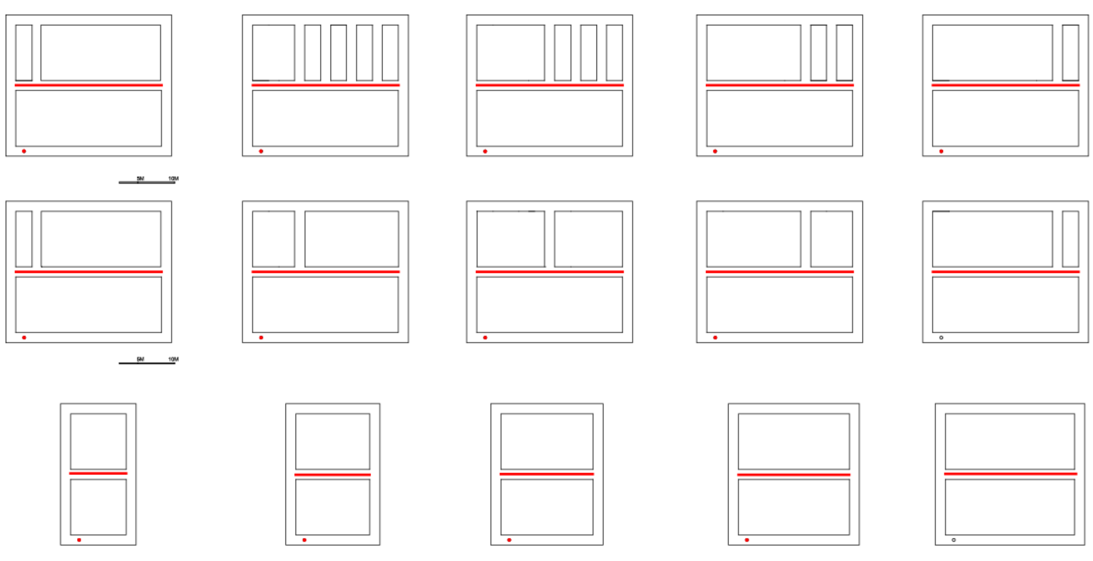
Figure 6.11 Plans of theoretical models grouped based *layout type*, *number of turns*, *number of branches*, *branch distance* and *corridor length* criteria.

Figure 6.11 (continued)

Test cases #3: race track design | 1 turn



Test cases #4: race track design |2 turns



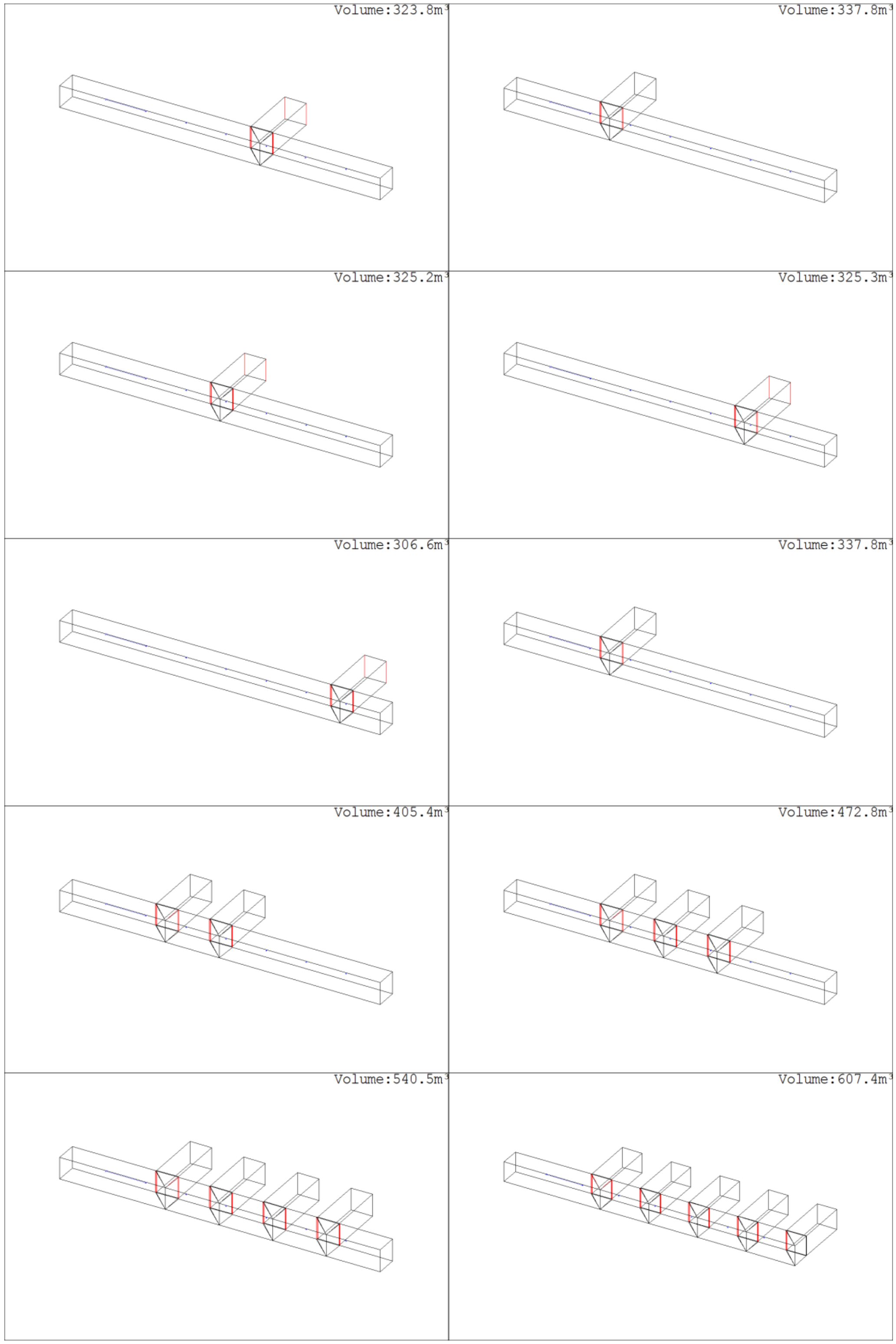


Figure 6.12 3D-CATT models of theoretical tree-like design hallways

Figure 6.12 (continued)

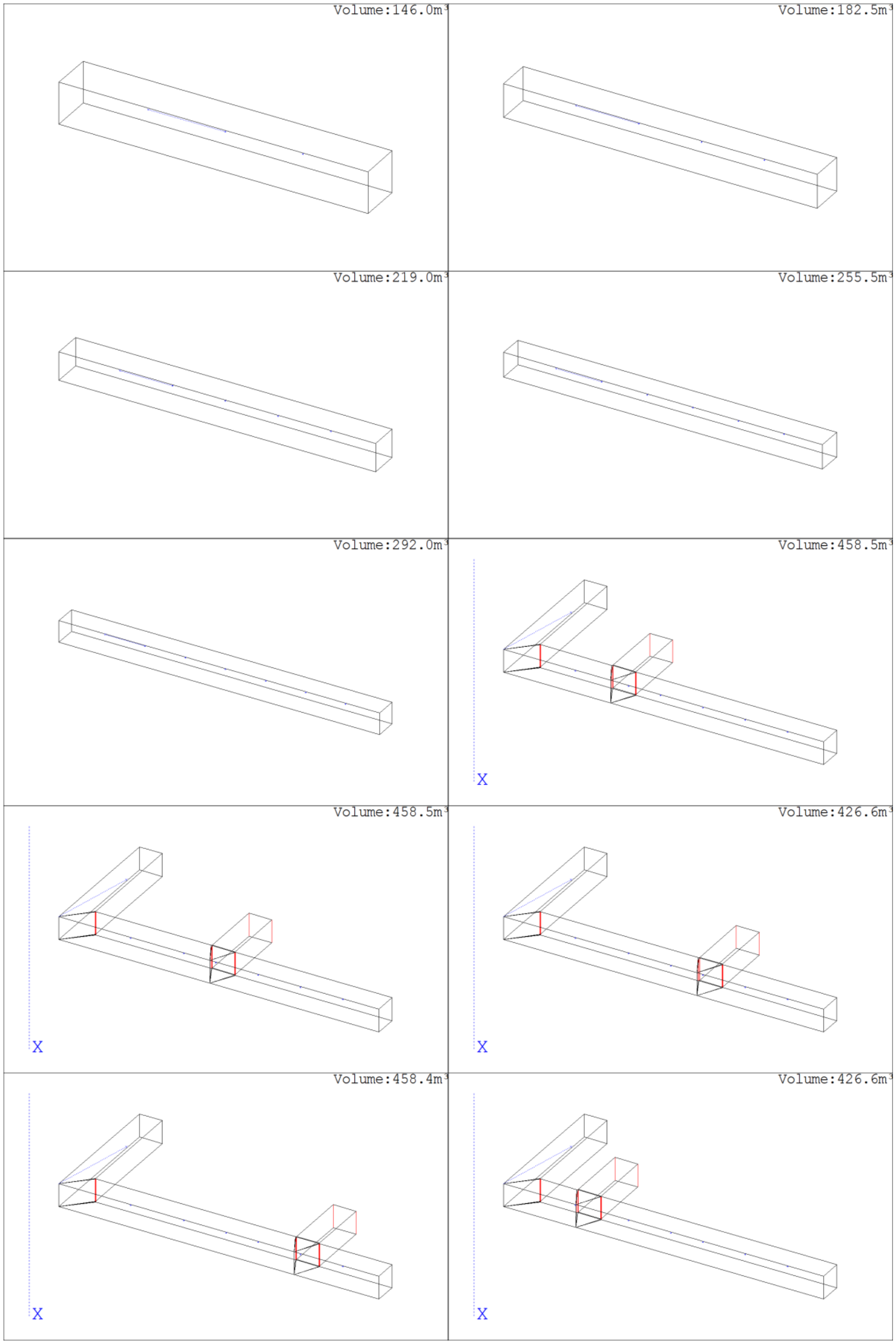
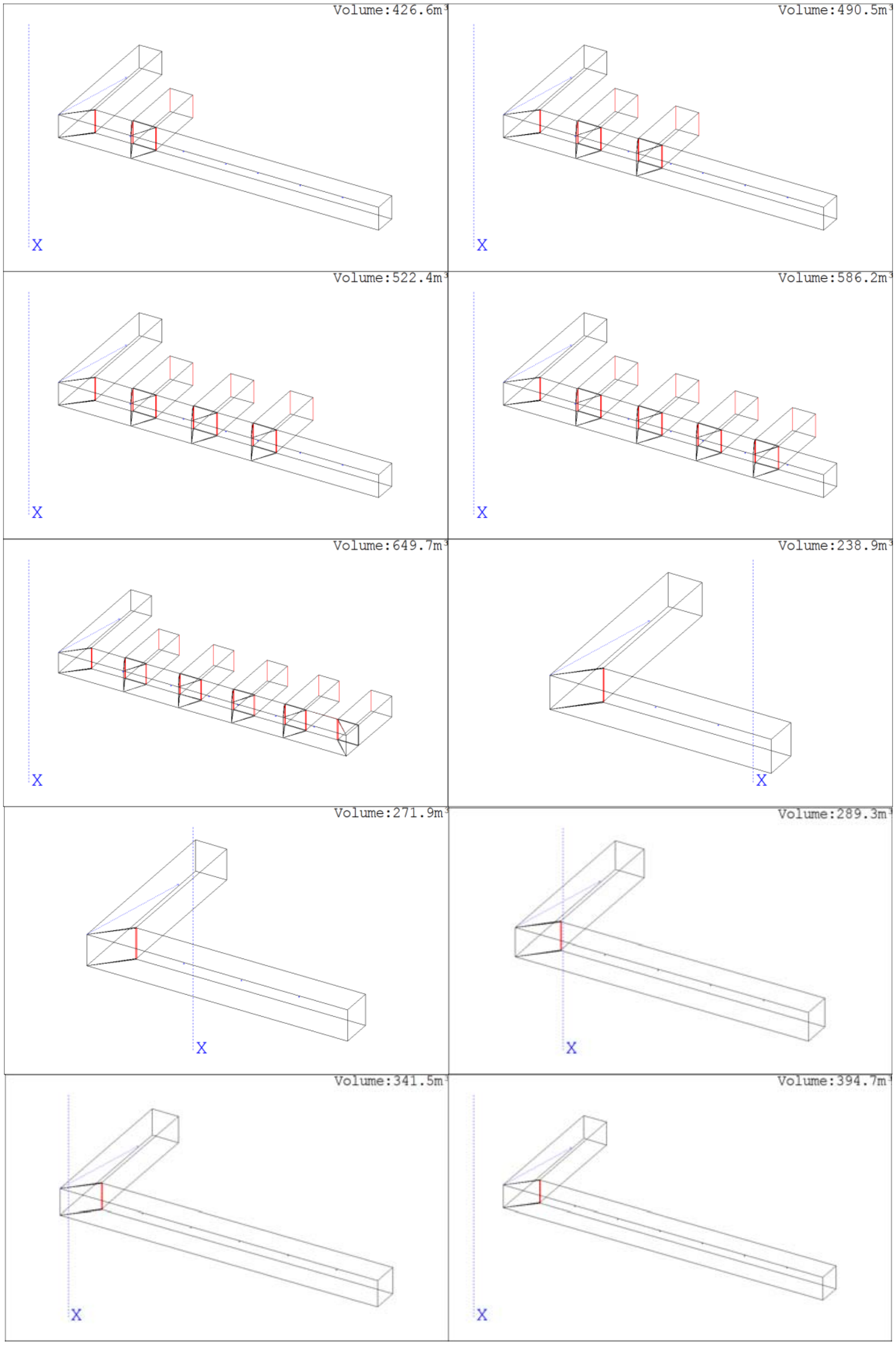


Figure 6.12 (continued)



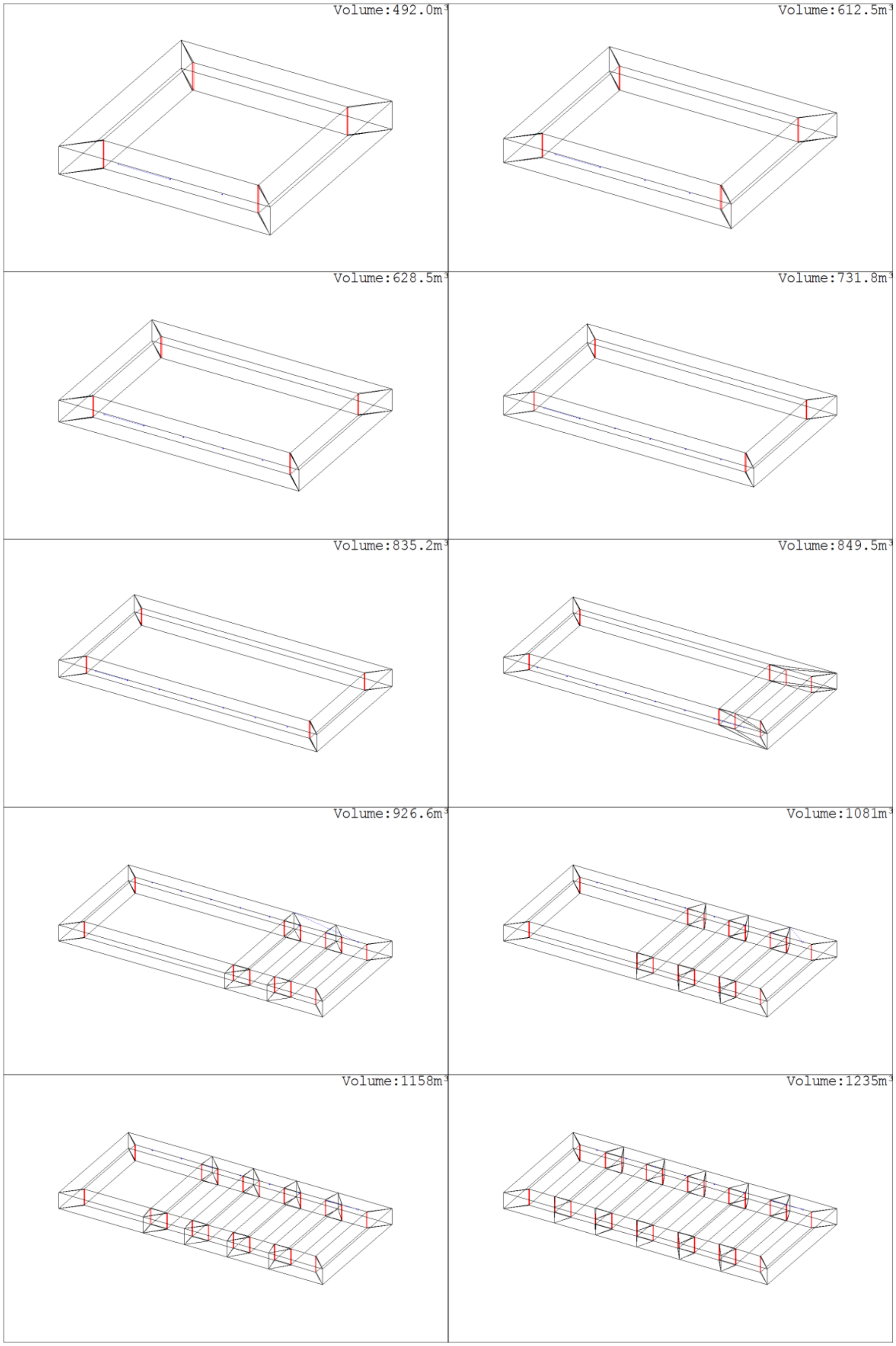


Figure 6.13 3D-CATT models of theoretical race track design hallways

Figure 6.13 (continued)

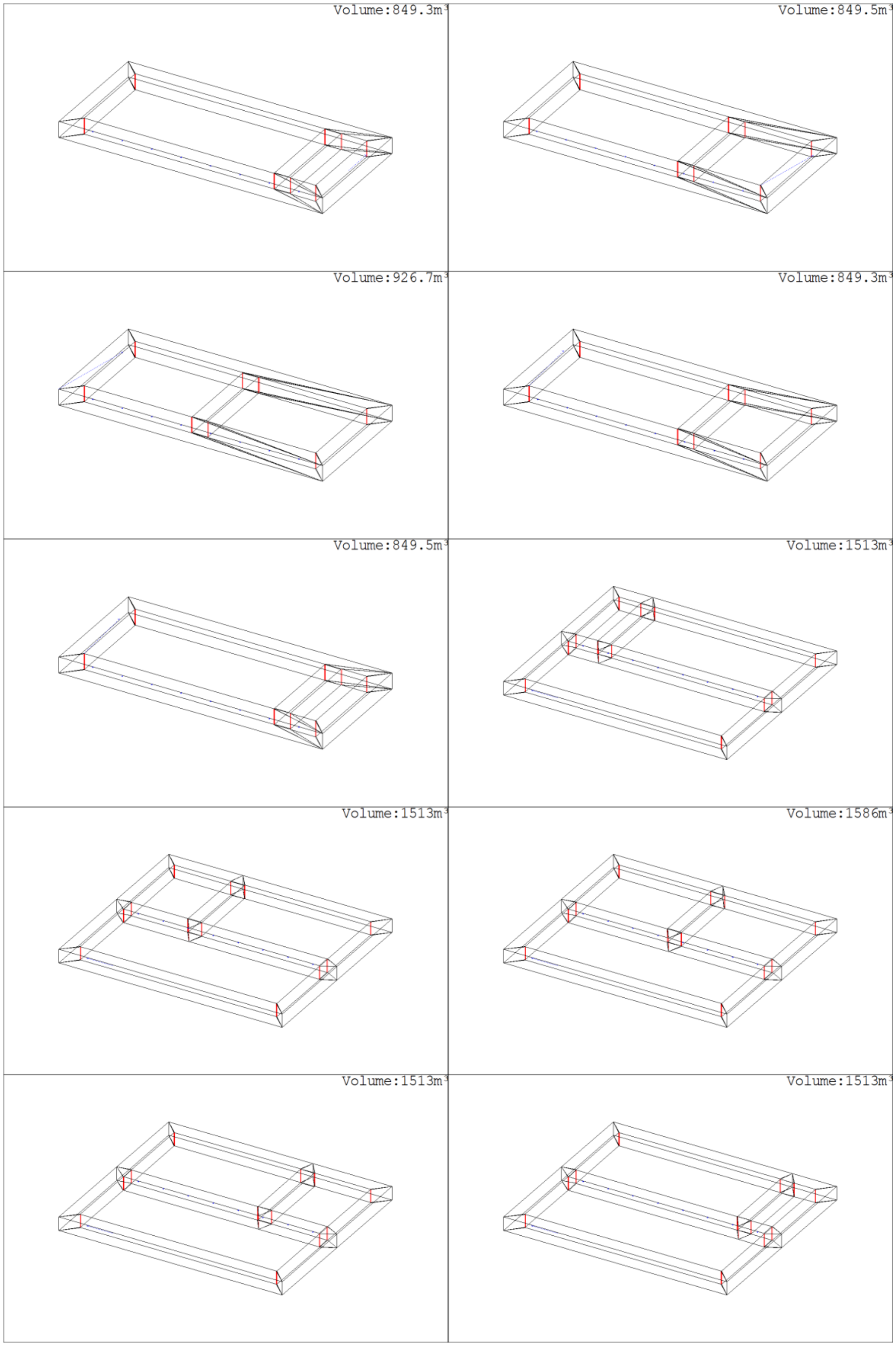
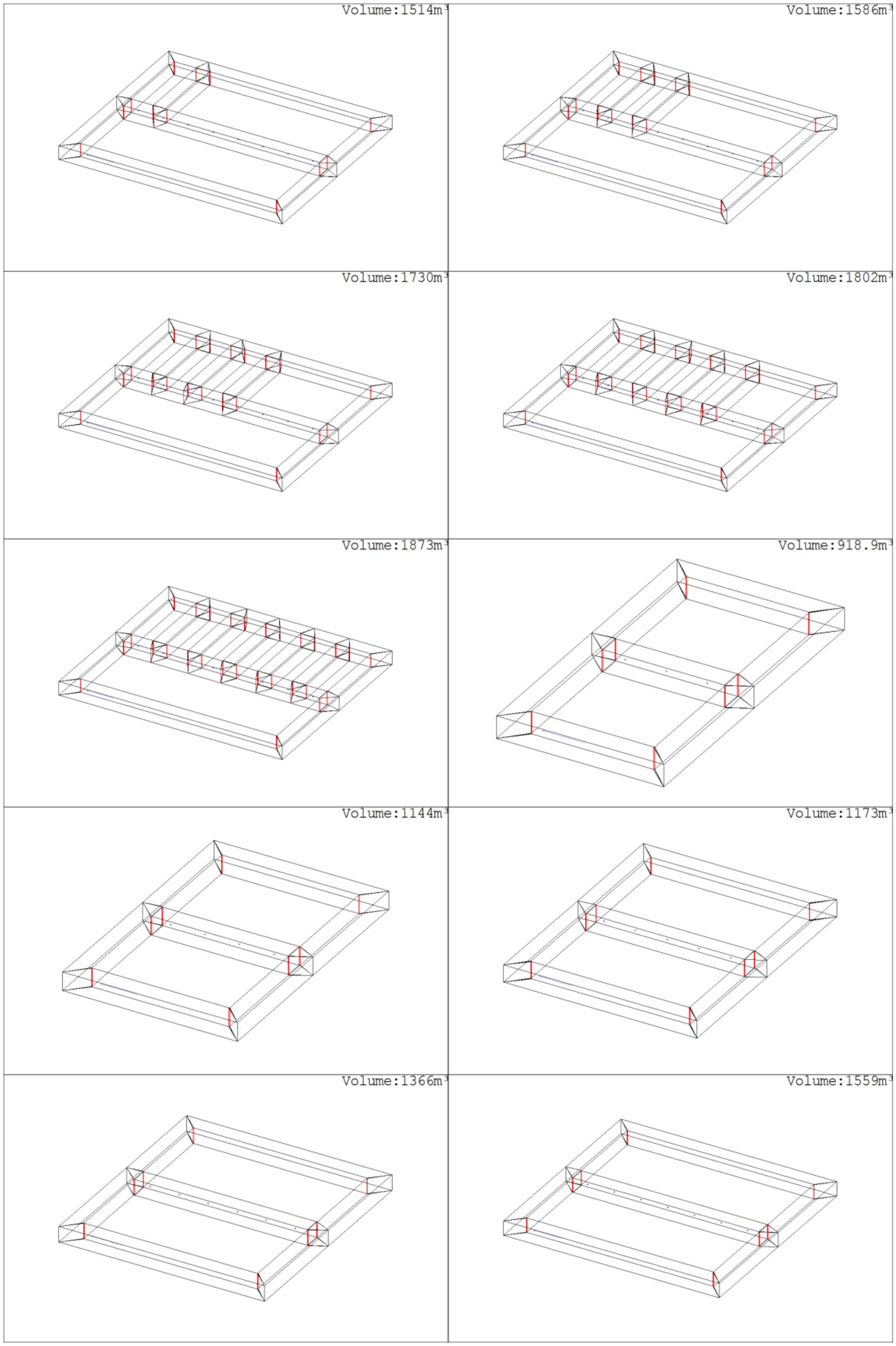


Figure 6.13 (continued)



6.3.3 Findings

First, 8 different partial correlation analyses are conducted. For each analysis, 15 theoretical models are considered. Design characteristics of each sample group are summarized in Table 6.3.

Table 6.3 Design characteristics of theoretical model groups

Layout design	**Surface material**	**Number of turns**	**Number of theoretical models**
Tree-like design	Absorption coefficient=0.3	1 turn	15 cases
Tree-like design	Absorption coefficient=0.3	2 turns	15 cases
Tree-like design	Absorption coefficient=0.1	1 turn	15 cases
Tree-like design	Absorption coefficient=0.1	2 turns	15 cases
Race track design	Absorption coefficient=0.3	1 turn	15 cases
Race track design	Absorption coefficient=0.3	2 turns	15 cases
Race track design	Absorption coefficient=0.1	1 turn	15 cases
Race track design	Absorption coefficient=0.1	2 turns	15 cases

Overall, findings of this follow up study agree with the earlier findings of the pilot study introduced in Section 6.2. In the first analysis, all theoretical models are applied with absorption coefficient = 0.1 and in the second analysis all theoretical models are applied with absorption coefficient = 0.3. As shown in Table 6.4-Table 6.5, *corridor length* is positively and significantly correlated with mean (averaged) reverberation time values. This finding suggests that overall receivers in the longer hallways are likely to experience longer reverberation time values. *Number of branches* is negatively and significantly correlated with the mean reverberation time values. This finding suggest that as the number of hallways (a.k.a. branch) connected to a particular core hallway increase, overall reverberation time values in that particular core hallway are expected to decrease.

Another analysis is conducted to assess whether the way hallways are connected to a particular hallway affect reverberation time values though the variable *branch distance*. The findings indicate that the distance between the branch and the closest hallway parallel to it is positively correlated with mean reverberation time values. However these correlations are not statistically significant. Consistent with the pilot study findings, *number of turns* is also positively and significantly correlated with mean reverberation time values when controlled for interfering design factors. This finding suggests that as the receivers navigate to corridors with higher number turns from the sound source, they are likely to experience increased reverberation time.

Based on beta values included in Table 6.4 and Table 6.5, the effect size of the *number of turns* variable is the highest compared to other design variables including *corridor length*, *number of branches* and *branch distance*. The interpretation is that one unit change in number of turns will potentially lead to more increase/decrease in RT30 compared to one unit change in *corridor length*, *number of branches* and *branch distance.* The *corridor length* variable has the second highest effects size. The interpretation is that one unit change in *corridor length* will potentially lead to more increase/decrease in RT30 compared to one unit change in *number of branches* and *branch distance. Number of branches* variable has the third highest effect size on the mean RT30.The interpretation is that one unit change in *corridor length* will potentially lead to more increase/decrease in RT30 compared to one unit change in *branch distance.*

Based on beta values represented in Table 6.4 and Table 6.5, changes in RT30 associated with one unit change in the *number of turns, corridor length*, *number of branches* and *branch distance* range between 0.01-0.57s. According to ISO standards, a minimum of 5% increase in RT30 is noticeable. Therefore, design interventions that lead to a minimum of 5% increase/decrease in the existing RT30 levels will lead to noticeable changes in RT30.

Table 6.4 Partial correlation analysis results **(**showing the strength of the relationship between different corridor design variables and reverberation time values in hallways with absorption coefficient = 0.3 surface materials. The sample group consisted of 60 theoretical models)

Absorption coefficient = 0.3		**Control variable**	**Frequency**	**Number of cases**	**Mean-RT Partial Correlation**	**Beta Values**
All cases	Length	Branch number Branch distance Layout type Turn Volume Ave dist.	500Hz	N=60	0.25* (p=0.066)	0.32*
			1kHz	N=60	0.24* (p=0.075)	0.33*
	Branch number	Length Branch distance Layout type Turn Volume Ave dist.	500Hz	N=60	-0.23* (p=0.099)	-0.28*
			1kHz	N=60	-0.23* (p=0.090)	-0.30*
	Branch distance	Length Branch number Layout type Turn Volume Ave dist.	500Hz	N=60	0.01 (p=0.96)	0.01
			1kHz	N=60	0.08 (p=0.57)	0.10
	Turn	Branch number Branch distance Layout type Length Volume Ave dist.	500Hz	N=60	0.24* (p=0.084)	0.52*
			1kHz	N=60	0.25* (p=0.073)	0.57*

* The correlation between variables is statistically significant at 0.1 level (p<0.1).

Table 6.5 Partial correlation analysis results (showing the strength of the relationship between different design variables and reverberation time values in hallways with absorption coefficient = 0.1 surface materials. The sample group consisted of 60 theoretical models)

Absorption coefficient = 0.1		**Control variable**	**Frequency**	**Number of cases**	**Mean-RT Partial Correlation**	**Beta values**
All cases	Length	Branch number Branch distance Layout type Turn Volume Ave dist.	500Hz	N=60	0.24* (p=0.078)	0.27*
			1kHz	N=60	0. 23* (p=0.082)	0.30*
	Branch number	Length Branch distance Layout type Turn Volume Ave dist.	500Hz	N=60	-0.23* (p=0.096)	-0.25*
			1kHz	N=60	-0.20* (p=0.094)	-0.29*
	Branch distance	Length Branch number Layout type Turn Volume Ave dist.	500Hz	N=60	0.01 (p=0.96)	0.01
			1kHz	N=60	0.03 (p=0.85)	0.03
	Turn	Branch number Branch distance Layout type Length Volume Ave dist.	500Hz	N=60	0.27* (p=0.052)	0.53*
			1kHz	N=60	0.26* (p=0.058)	0.57*

* The correlation between variables is statistically significant at 0.1 level (p<0.1).

6.4 EMPIRICAL STUDY 2

LINKING ACOUSTICS AND DESIGN METRICS OF 20 THEORETICAL FLOOR PLATE MODELS

6.4.1 Scope

Empirical Study 1 analyzed the relationship between design characteristics and reverberation time of 60 theoretical models developed from heuristic analyses. Empirical Study 1 focused on the effects of design features of particular hallways located in complex inter-connected corridor systems such as *corridor length, number of branches*, etc. Instead of design qualities of particular hallways, this part of the study focuses on the effects of overall floor-plate shape qualities of nursing unit corridors by using two new floor-plate shape metrics. Furthermore, instead of the 60 theoretical corridor models, empirical study 2 utilizes 20 new theoretical floor plate models.

6.4.2 Methodology

The two new design metrics introduced are used to quantify shape characteristics of corridor floor-plates: visual fragmentation (VF) and relative grid distance (RGD) (Shpuza, & Peponis, 2008). Floor-plate design metrics introduced in Chapter 6.3 are used to quantify design qualities of particular hallways in a corridor system. In this section, the RGD and VF are used to quantify shape qualities of the entire corridor floor-plates. *Relative grid distance* (RGD) values represent the degree to which a floor-plate shape diverges from square with regard to total distances between pairs of locations in the shape. Square is assigned the smallest RGD value of 1. Higher RGD values indicate more elongated floor-plate shapes. *Visual fragmentation* (VF) values reflect the convexity of a floor-plate shape as the amount of directional changes needed to connect any two locations on the floor-plate. Visual fragmentation values range between 0 and 1. VF value of 0 is assigned to any convex shaped floor-plate. Higher visual fragmentation values indicate more fragmented/jagged floor-plate shapes and those with holes.

Studies exploring the relationship between of floor-plate design and acoustics have mostly considered simple floor-plate shape metrics like width-to-length ratio. Even though these metrics have been successfully used for the shape analysis of simple floor-plate shape geometries, they do not provide a comprehensive picture of the complex floor-plate shape qualities such as fragmentation and compactness. RGD and VF are chosen because these two metrics have been successfully used for the quantification of complex floor-plate shape qualities as they relate to key programmatic considerations such as the layout of work stations (Shpuza, & Peponis, 2008). Moreover, the underlying logic of RGD and VF involves computing distance between grid cells and computing the number of turns. Whereas these were initially developed because of their potential social and programmatic impacts, there are in fact the same considerations that impact the sound environment. One of the correspondences is related with similarities between path distance considerations. For RGD calculations, a floor-plate is represented with a grid system. RGD calculations take into account every possible distance needed to connect each cell to all other cells located in the grid system. Interestingly, when sound rays are emitted by the sound source, they travel different distances till they get to the receiver`s ear. It is mainly because each sound ray is reflected by a different combination of boundary surfaces. The other correspondence is related with similarities between directional change considerations. VF calculations take into account all directional changes needed to connect any two locations on the grid system. It is also well known that directional changes (a.k.a. turns) leads to some changes in the behavior of sound.

To explore the relationship between RGD, VF and RT30, 20 different theoretical design models are developed based on the heuristic design analysis of nursing unit corridor floor-plates (Figure 6.14). As shown in Figure 6.9, the total corridor length of nursing unit corridor clusters mainly range between 30m to 120m. Mid range total corridor length value of 66m/216ft is assigned to all theoretical models. The width of the nursing unit corridors range between 2m to 4.7m but most times it is about 3m. Therefore, the width of the theoretical corridors is set to 3m.

As shown in Figure 6.5, about 2/3rd of the nursing unit corridor clusters are tree-like design corridors and the rest of them are race track design corridors. In this analysis, all of the theoretical models are examples of tree-like corridor design. Theoretical models with more complex floor-plate shapes are purposefully excluded from the sample group; particularly because RGD and VF values have not varied sufficiently for corridors with more complex floor-plate shapes. The complexity of floor-plate shapes of the nursing unit corridor clusters varied. For the same reason, floor-plate shapes of the theoretical models are also designed to have different levels of geometric complexity. Ten of them are composed of a single hallway with different floor-plate shapes. The rest of them are composed of two main hallways connected with another hallway as shown in Figure 6.14. The number of intersecting corridor parts range from 2 to 6. This number is quite similar to the number of the intersecting corridor parts of the nursing unit corridor clusters as shown in Figure 6.5.

RGD and VF shape metrics have been used for the quantification of floor-plate shape characteristics of office spaces; however, they have not been used for the floor-plate shape analysis of long enclosures. This study tests the applicability of these two design metrics for floor-plate shape analysis of long enclosures and analyzes the association between design and acoustics of corridors by considering these two metrics.

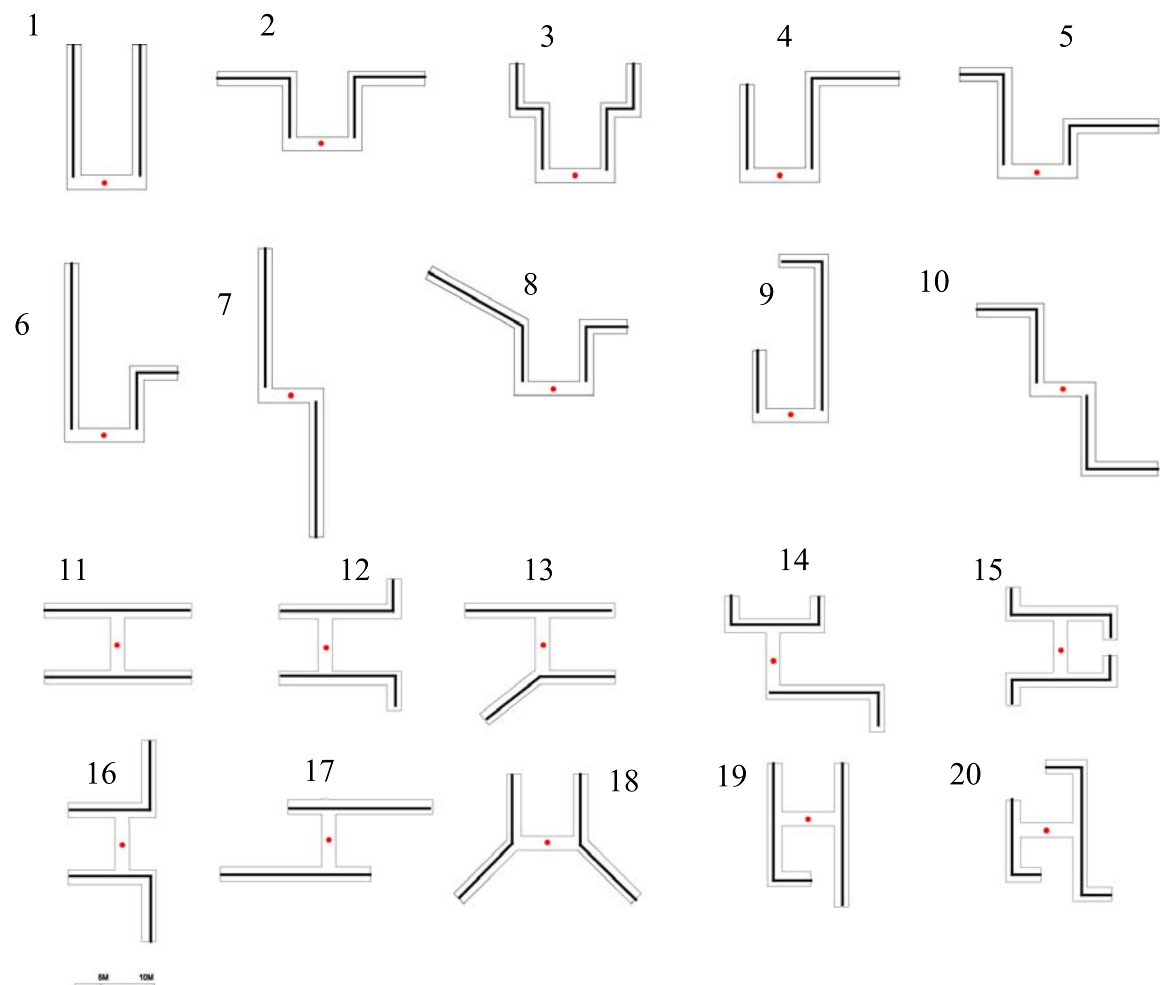


Figure 6.14 Floor plans of theoretical corridor models with different floor-plate shape qualities

Acoustic characteristics of the theoretical models are analyzed with CATT acoustic modeling program. A sound source (represented with a red dot) is located at the center of the *connecting* corridor as shown in Figure 6.14. In this analysis two considerations are taken into account to control for the effects of direct sound on reverberation time values. First, the length of the hallway where the sound source is located is kept the same (10m/33ft) in all theoretical models. Second, only non-visual sound field characteristics are reported in the acoustic analysis of these theoretical models. Multiple receivers are systematically distributed 5m (16.4ft) apart from each other along the highlighted paths located in the non-visual sound fields of the theoretical models.

6.4.3 Findings

Two partial correlation analyses are conducted to assess the individual effects of VF and RGD on mean reverberation time values. The reverberation time of each theoretical model is represented with a single number. This single number is calculated by averaging the reverberation time values calculated for each receiver located in the non-visual sound field. The floor plate design variables of VF and RGD of each theoretical model are also represented with single numbers provided by Qelize (www.morpostudio.net/qelize). Qelzie is a Java applet designed for calculating the shape measures of RGD and VF.

According to analysis results as shown in Table 6.6, *relative grid distance* is positively and significantly correlated with mean reverberation time values. This finding suggested that as the floor-plate shape gets more elongated, averaged reverberation time values are expected to increase. Interestingly, this finding is consistent with earlier findings of this study. Elongated corridors potentially have longer corridors and according to previous study findings reverberation time values are likely to be higher in the corridors with higher *corridor length*.

In addition, *visual fragmentation* is negatively and significantly correlated with mean reverberation time values. This finding suggests that as the shape gets more fragmented/ jagged, reverberation time values are likely to decrease. This finding can also be expected based on the earlier study findings. Given the same total corridor length, more fragmented long enclosures potentially have shorter individual corridors and in corridors with shorter corridor length, reverberation time values are likely to be lower. Similarly, a higher *number of branches* potentially results in more fragmented long enclosures. In the empirical study 1, the *number of branches* is found to be significantly and negatively correlated with reverberation time values.

Linear regression analysis is also conducted to assess the amount of variance caused by the RGD and VF characteristics of the floor-plate shapes. As shown in Table 6.7, 75% of the variance in reverberation time values (specifically for 500Hz) is explained with VF and RGD. The variance accounted for is 65% at 1kHz. For visual assessment of the correlation between floor-plate metrics and mean reverberation time values, scatter-plots are also generated as shown in Figure 6.15 and Figure 6.16.

Table 6.6 Partial correlation coefficients showing the strength of the relationship between floor-plate shape characteristics (RGD + VF) and reverberation time.

	Control variables	**Mean-RT30 (500Hz) Partial Correlation**	**Mean-RT30 (1kHz) Partial Correlation**
Visual fragmentation	RGD	-0.70*	-0.60*
Relative grid distance	VF	0.80*	0.75*

* The correlation between variables is statistically significant at 0.05 level (*p* <0.05).

Table 6.7 Regression analysis results

	R2 (500Hz)	**Beta values (500Hz)**	**R2 (1kHz)**	**Beta values (500Hz)**
Visual fragmentation (VF) Relative grid distance (RGD)	75%	-0.29 (*p*<0.05) 0.06 (*p*<0.05)	65%	-0.27 (*p*<0.05) 0.06 (*p*<0.05)

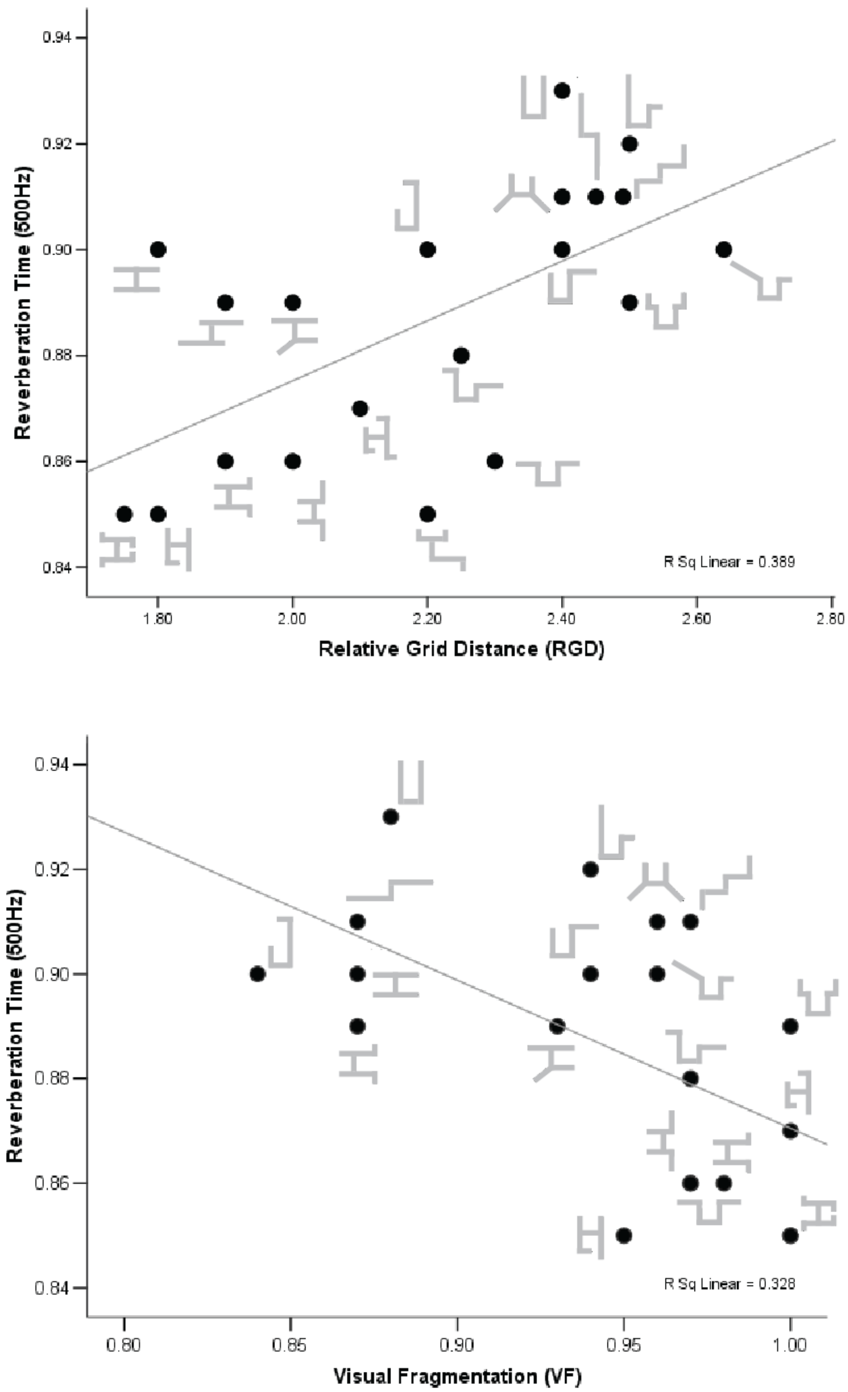
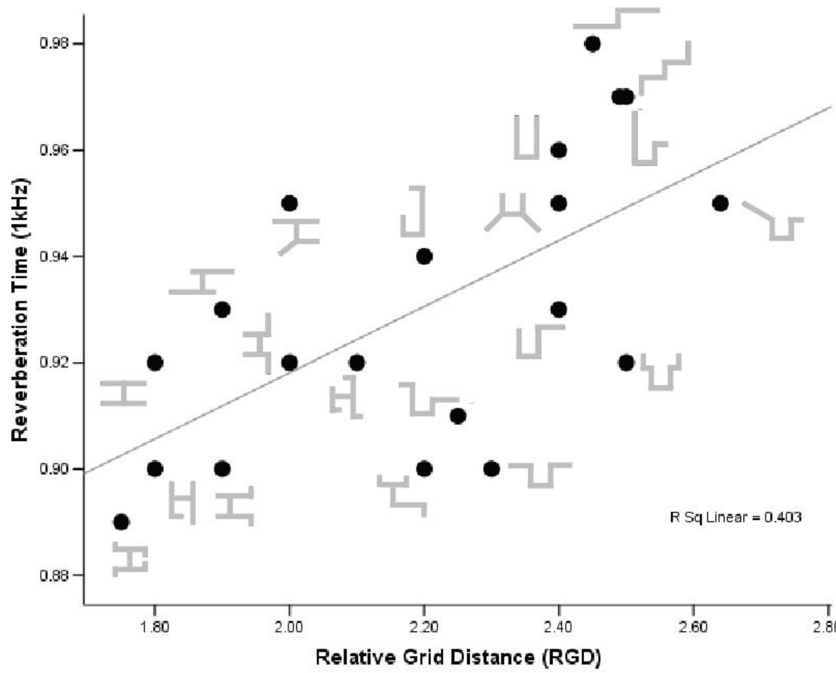


Figure 6.15 Scatter plots showing the relationship between RGD + VF and RT30 at 500Hz.



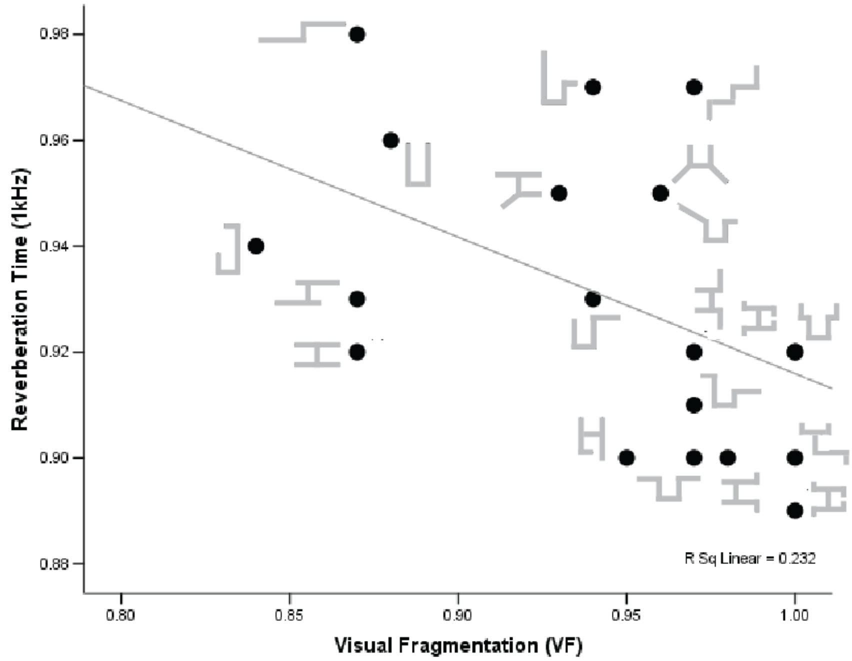


Figure 6.16 Scatter plots showing the relationship between RGD + VF and RT30 at 1kHz

A follow up analysis is conducted to explore the relationship between visual fragmentation, relative grid distance and RT30. As shown in Table 6.8, bivariate correlation analysis results indicate that VF and RGD values are not significantly related. For visual assessment of the correlation between floor-plate shape metrics and mean reverberation time values, scatter-plots are also generated as shown in Figure 6.17 and Figure 6.18. In these scatter-plot graphs, two real world hospitals are also included in addition to 20 theoretical models. Like theoretical models, acoustic qualities of these two real world hospitals are analyzed with CATT acoustic modeling program. Mean RT30 is consistently and significantly higher in the two real world hospitals compared to the theoretical models. This is probably related with significant differences between the total corridor lengths of the two real world hospitals and theoretical models.

Table 6.8 Bivariate correlation analysis results

Bivariate correlation	Relative grid distance
Visual fragmentation	0.01 ($p>0.05$)

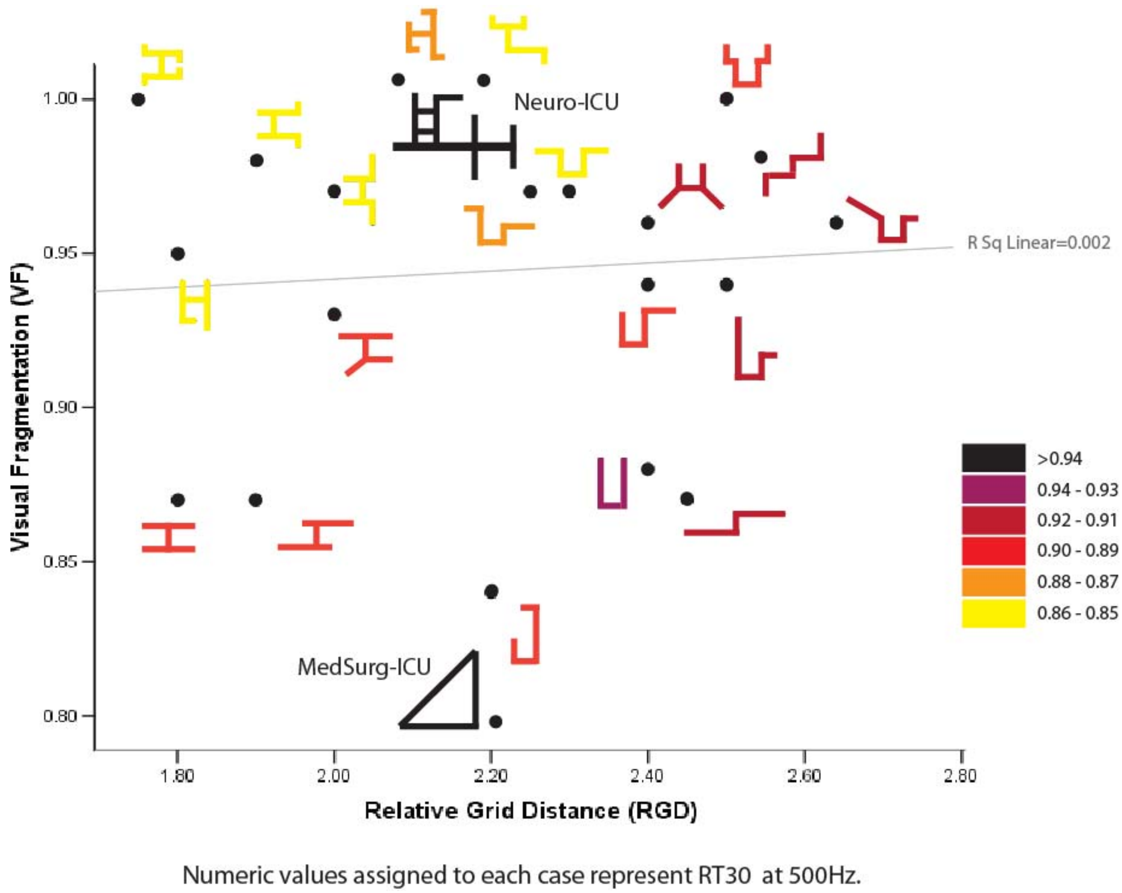


Figure 6.17 Scatter plots showing the relationship between RGD, VF and RT30 at 500Hz. (MedSurg-ICU (VF=0.8, RGD=2.2, RT30= 1.75); Neuro-ICU (VF=1; RGD=2.2, RT30=1.80)).

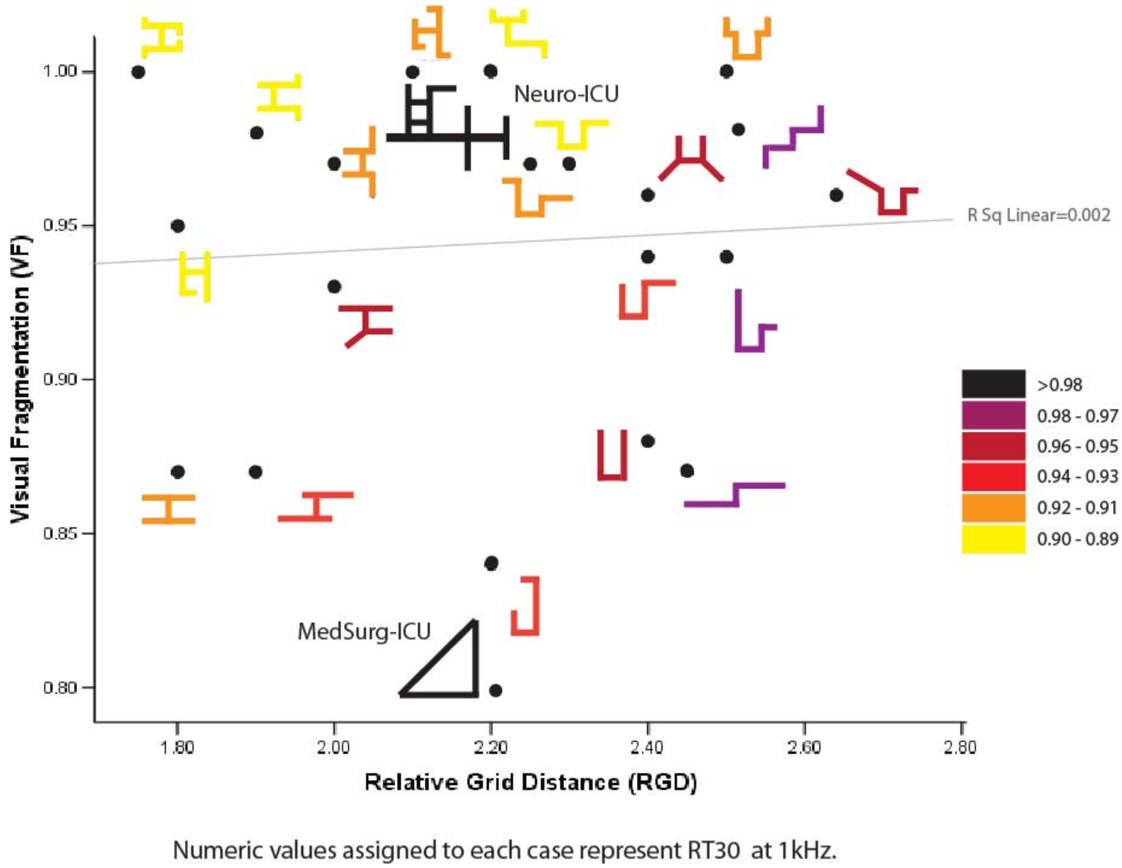


Figure 6.18 Scatter plots showing the relationship between RGD, VF and RT30 at 1kHz. (MedSurg-ICU (VF=0.8, RGD=2.2, RT30=1.80); Neuro-ICU (VF=1; RGD=2.2, RT30=1.90)).

6.5 DISCUSSION

The experimental studies introduced in Chapter 6 have statistically analyzed the relationship between design and acoustic qualities of inter-connected corridors by conducting heuristics design analysis, floor-plate shape analysis, field measurements, acoustic simulations and statistical analyses. The summary of these empirical study findings can be found in Table 6.9. More detailed discussion about these findings can be found in the following paragraphs.

Corridor Design Variable	Impact on Reverberation
Increased Number of Turns	Increased Mean RT
Increased Corridor Length	Increased Mean RT & SD
Increased Number of Branches	Decreased Mean RT
Increased Branch Distance	Decreased SD
Increased Relative Grid Distance	Increased Mean RT
Increased Visual Fragmentation	Decreased Mean RT

Table 6.9 Summary of the empirical study findings conducted in Chapter 6

The main motivation of these empirical studies is to assess how different aspects of corridor floor-plate design of nursing units impact reverberation times. Reverberation time is one of the critical acoustic measures predicting the effectiveness of critical sound tasks by caregivers such as critical conversations and auditory monitoring. Particularly, in critical care units, caregivers continuously assess and localize auditory cues. Previous study findings indicate that the capability of the human auditory system to monitor and localize sounds is reduced in sound environments with long reverberation times.

A pilot study is conducted in the inter-connected corridors of several educational settings. An impulse response measurement method is used to assess the acoustic characterstics of these corridor settings. The pilot study findings suggest the potential significant impact of design features of particular hallways (e.g., number of turns, corridor length, and number of branches) on reverberation time values. For example, according to findings of the study, in the hallways that are 2 turns away from the sound source, averaged reverberation time values are likely to be higher compared to hallways 1 turn away from the sound source. Moreover, in the longer corridors averaged reverberation time values are likely to be higher compared to shorter corridors. On the other hand, in the hallways with higher number branches, the reverberation time values are expected be lower compared to hallways with lower number of branches.

To test the findings of the pilot study, Empirical Study 1 is designed to be a more controlled follow up study using CATT acoustic simulation program. Based on heuristic analysis of the existing nursing unit corridors, 80 different theoretical models with different design implementations are generated and in total 140 acoustic simulations are conducted. Findings of Empirical Study 1 are quite similar to the pilot study findings. For example, corridor length of the hallways located in the non-visual sound fields is significantly and positively correlated with averaged reverberation time values. In constrast, number of branches variable is significantly and negatively correlated with reverberation time values.

Empirical Study2 is conducted to assess the effects of additional floor-plate shape characteristics of inter-connected corridor systems on averaged reverberation time values. According to this analysis, RGD is positively correlated with mean reverberation time values and VF is negatively correlated with mean reverberation time values. Moreover, the relationhip between RGD and VF is not statistically significant.

CHAPTER 7

VALIDATION STUDY

7.1 SCOPE

The previous section has discussed the findings of the theoretical studies linking design and acoustics of inter-connected corridors. To assess whether theoretical study findings in Chapter 6 track with the study findings based on real-world hospital corridor geometries, a series of follow up studies is conducted. The acoustics and design of inter-connected corridors of the two real-world hospital wards is analyzed by conducting field measurements and acoustic simulation analysis.

7.2 METHODOLOGY

The design features of the two units are reviewed in detail in Section 2.2.2. Shortly, the Neurological ICU (Neuro-ICU) is a fairly new 20-bed unit. The Neuro-ICU has a tree-like design corridor system with long corridors. The total length of the hallways is 200m (656ft).

The Medical Surgical ICU (MedSurg-ICU) is a 1980s era 20-bed unit. The MedSurg-ICU has a triangular shape *race track* design corridor system with shorter corridors. The total length of the corridors is 80m (262ft).

In-situ impulse response measurements

Impulse response measurements are conducted to assess the reverberant qualities of the two ward corridors objectively (Figure 7.1). The impulse response measurements have taken place at 4 different receiver locations in two hallways in each ward as shown in Figure 7.2 and Figure 7.3.The preliminary measurements first have taken place in the non-visual sound field. However, these measurements have to be excluded as an adequate signal to noise ratio (SNR) could not be achieved. In the other non-hospital settings, the SNR can be improved by simply increasing the level of the driving sound signal. However, ICUs are noise sensitive settings and occupied 24/7. This limits the level of the driving sound signal for the impulse response measurement. In the MedSurg-ICU and Neuro-ICU, the critical distances are 3m (9.8ft) and 5m (16.4ft), respectively. At all times, the receivers are located beyond the critical distance. The distance between source and receivers are 8m (26ft) and 12m (39ft) in both wards. Detailed information about the impulse response measurement procedure can be found in Appendix G and Appendix H. During the measurements, all patient room doors are closed in both wards. All staff members including the directors of the both wards and the visitors are informed about the procedure.

Figure 7.1 Impulse response measurements in the hospital corridors

Figure7.2 Distribution of source and receiver locations in the Neuro-ICU

Figure 7.3 Distribution of source and receiver locations in the MedSurg-ICU

Acoustic simulation analysis

Idealized 3D acoustic models of the two real world ward corridors are also generated. The models allowed for control of the interfering effects of the differently distributed materials on the boundary surfaces. Original corridor lengths are assigned to 3D acoustic models of the two ward corridors. Acoustic simulation analysis of these corridors is conducted in 6 phases.

In phase 1, the impacts of T and cross shaped corridor intersections on reverberation time levels are tested (Figure 7.4). The analysis has taken place only in the corridors of the Neuro-ICU as there is no T-shaped configuration in the MedSurg-ICU. First, source 1 (S1) is activated and reverberation times at the R1 and R2 locations are recorded. Second, source 2 (S2) is activated and reverberation times at the R3 and R4 locations are recorded. The distances between source and receivers are kept the same for both test cases. To represent the acoustic conditions associated with the T shaped intersection, reverberation times predicted for receivers R1-R2 are averaged. Similarly, predicted results for receivers R3 and R4 are averaged to represent the acoustic conditions associated with cross shaped intersection.

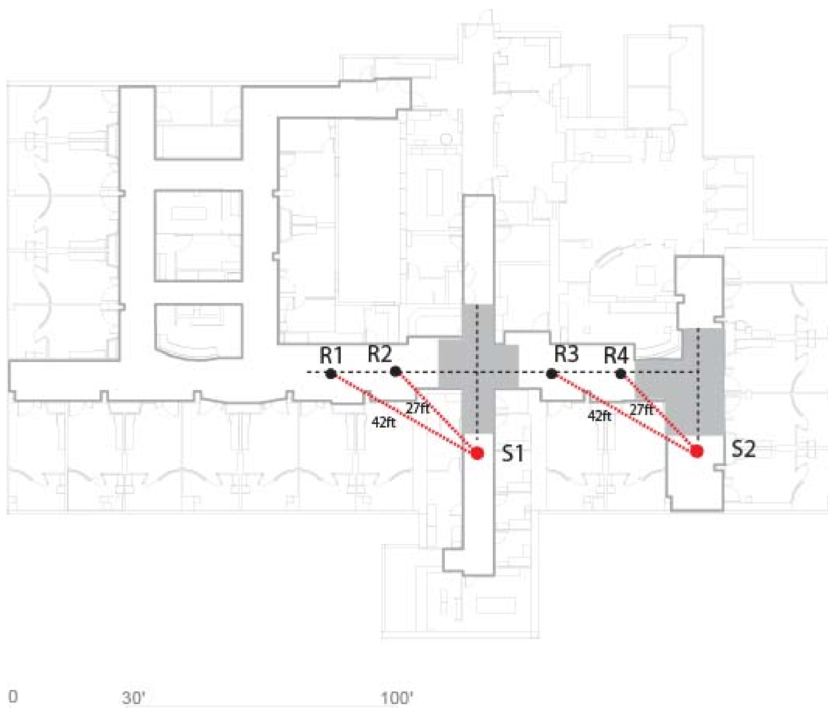


Figure 7.4 Source and receiver locations considered for the acoustic analysis of “T” and “cross” shaped intersections in the phase 1 Neuro-ICU simulations

In phase 2, the impact of number of branches on reverberation time is tested. The analysis has taken place in the corridors of both the Neuro-ICU and MedSurg-ICU (Figure 7.5-7.6). The receivers R1, R2 and R3 are located in one of the Neuro-ICU corridors with multiple branches (Figure 7.5); and receivers R3, R4 and R5 are located in one of the MedSurg-ICU corridors without any branches (Figure 7.6). Predicted RT30 levels for

R1-R2-R3 and R4-R5-R6 are averaged to represent the overall acoustic conditions along the Neuro-ICU corridor and the MedSurg-ICU corridor, respectively.

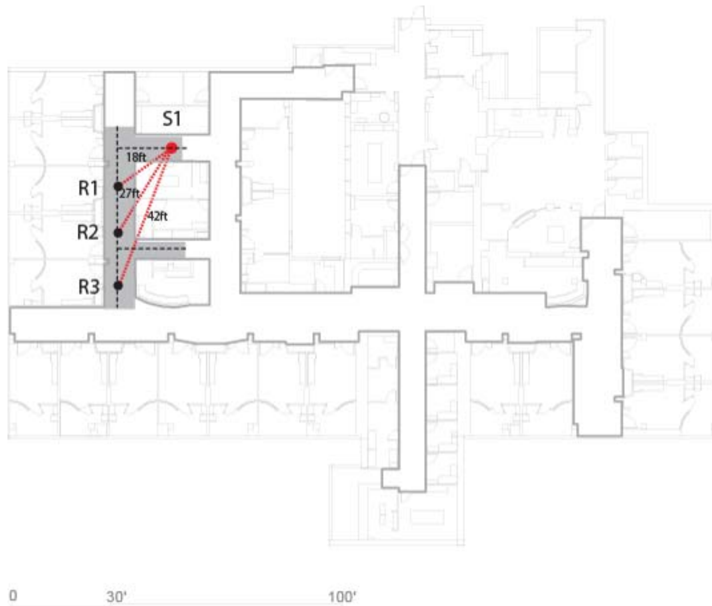


Figure 7.5 Distribution of source and receivers along the corridor with multiple branches in the phase 2 Neuro-ICU simulation

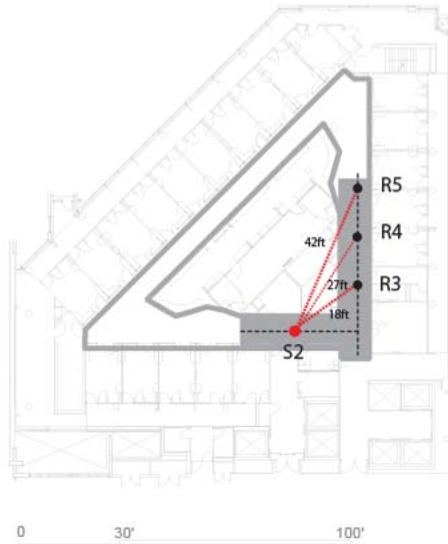


Figure 7.6 Distribution of source and receivers along the corridor without any branches in the phase 2 MedSurg-ICU simulation

In phase 3, the impact of *number of turns* on reverberation time is tested (Figure 7.7-7.8). In the Neuro-ICU, the receivers R1 and R2 are located along the corridor that was two turns away from the sound source (Figure 7.7). In the MedSurg-ICU, the receivers R3 and R4 are located along the corridor that is one turn away from the sound source (Figure 7.8). The distances between source and receivers are kept the same in the Neuro-ICU and MedSurg-ICU. Predicted results for R1-R2 and R3-R4 are averaged to represent the overall reverberant qualities of the corridors, respectively.

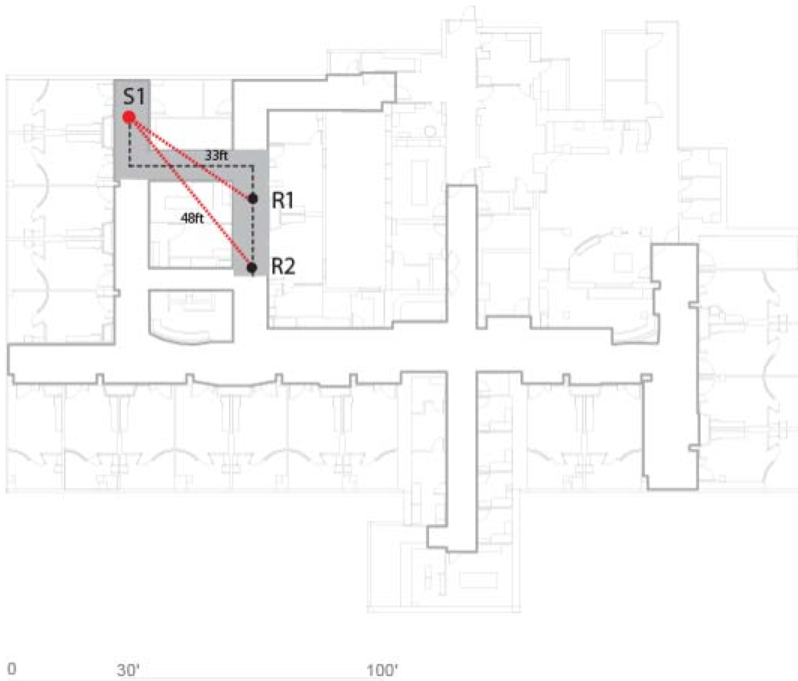


Figure 7.7 Distribution of source and receivers that are 2 turns away from the source in the phase 3 Neuro-ICU simulation

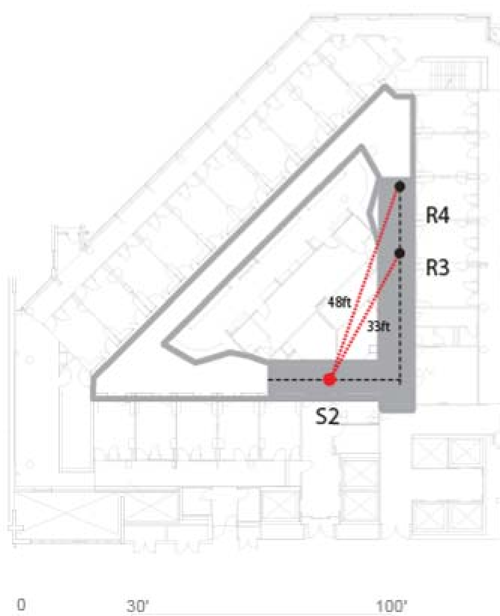


Figure 7.8 Distribution of source and receivers that are 1 turn away from the source in the phase 3 MedSurg-ICU simulation

In phase 4, the impact of corridor length on reverberation time is tested (Figure 7.9-7.10). In the Neuro-ICU, receivers R1 and R2 are placed along the longest corridor (Figure 7.9). In MedSurg-ICU, receivers R3 and R4 are placed along a shorter corridor (Figure 7.10). Receivers R1-R2 and R3-R4 are averaged to represent the overall acoustic conditions along the corridors in Neuro-ICU and MedSurg-ICU, respectively.

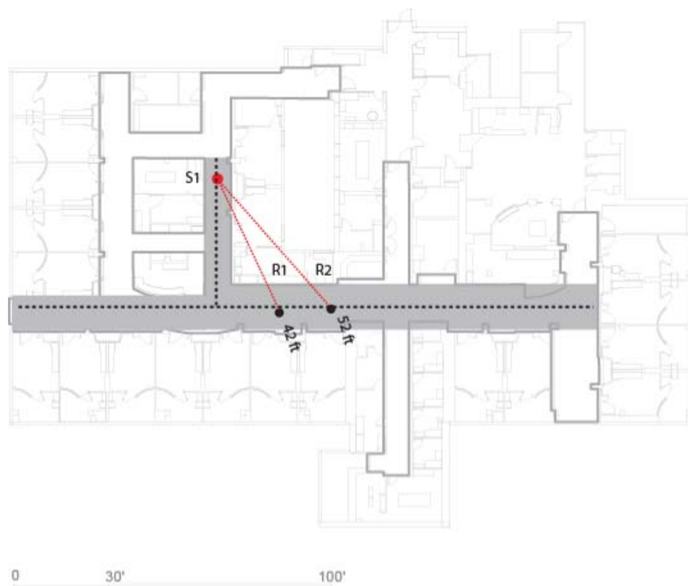


Figure 7.9 Distribution of source and receivers along a long corridor in the phase 4 Neuro-ICU simulation

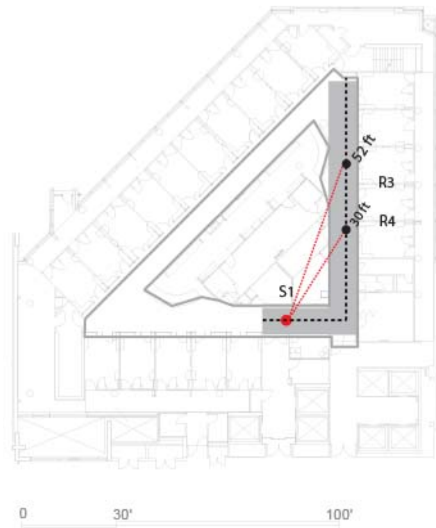


Figure 7.10 Distribution of source and receivers along a shorter corridor in the phase 4 MedSurg-ICU simulation

In phase 5, the impact of *overall corridor design* on reverberation time is tested by placing the receivers in different corridors of each unit (Figure 7.11-7.12). Visual fragmentation values for Neuro-ICU and MedSurg-ICU are 1.0 and 0.8, respectively. The interpretation is that floor-plate shape of the Neuro-ICU is more fragmented compared to floor-plate shape of the MedSurg-ICU. Relative grid distance value for Neuro-ICU and MedSurg-ICU is the same (2.2). In other words, floor-plate shapes of the Neuro-ICU and MedSurg-ICU is similarly elongated. Predicted reverberation time values for R1-R2-R3-R4-R5 are averaged to represent the acoustic conditions in the idealized corridors of the Neuro-ICU. Predicted reverberation time values for R6-R7-R8-R9-R10 are averaged to represent the acoustic conditions in the MedSurg-ICU corridors.

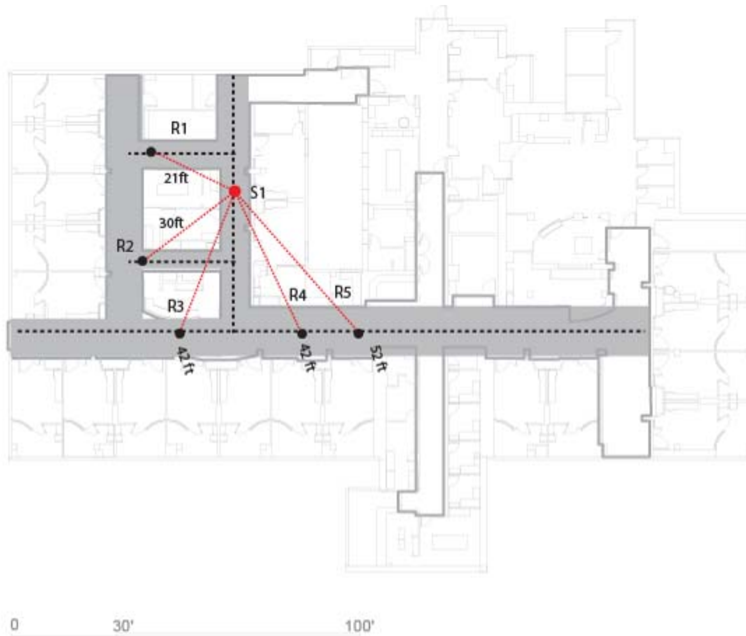


Figure 7.11 Distribution of source and receivers in the phase 5 Neuro-ICU corridor simulation

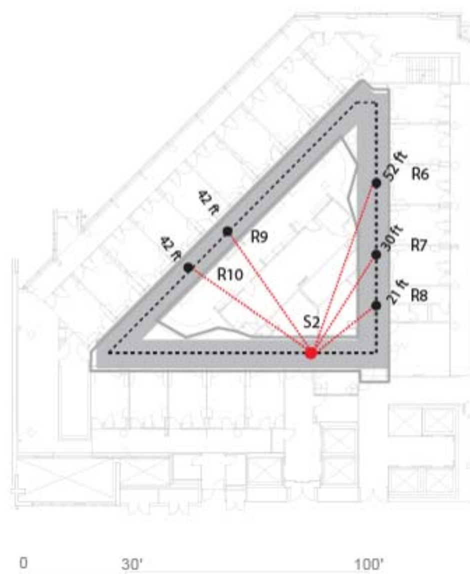


Figure 7.12 Distribution of source and receivers in the phase 5 MedSurg-ICU corridor simulation

Finally in phase 6, another analysis is conducted to test the impact of overall corridor design on reverberation time (Figure7.13-7.14). In this analysis, an idealized version of the Neuro-ICU floor-plate design is considered instead of the original floor-plate design used in the previous phase 5 analysis (Figure 7.13). The original design of the MedSurg-ICU corridors remained unchanged (Figure 7.14). The motivation is to test the impact of two different corridor designs with similar total corridor length. Visual fragmentation values for the idealized design of the Neuro-ICU and MedSurg-ICU is 1.0 and 0.8, respectively. The interpretation is that the idealized floor-plate shape of the Neuro-ICU is more fragmented compared to the floor-plate shape of the MedSurg-ICU. The relative grid distance values for the idealized floor-plate shape of the Neuro-ICU and MedSurg-ICU are 1.9 and 2.2. In other words, the floor-plate shape of the MedSurg-ICU is more elongated. Predicted reverberation time values for R1-R2-R3-R4-R5 are averaged to represent the acoustic conditions in the idealized corridors of the Neuro-ICU. Predicted reverberation time values for R6-R7-R8-R9-R10 are averaged to represent the acoustic conditions in the MedSurg-ICU corridors.

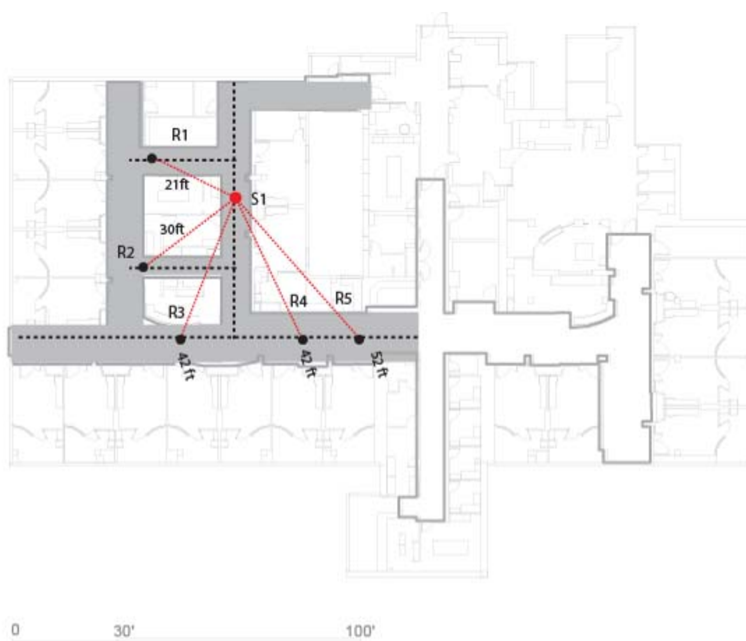


Figure 7.13 Distribution of source and receivers in the phase 6 idealized Neuro-ICU corridor simulation

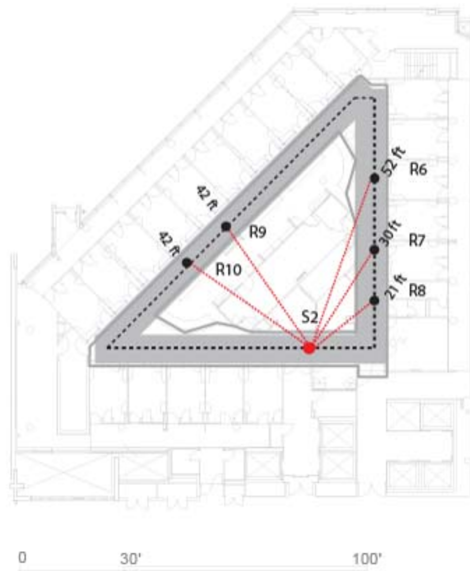


Figure 7.14 Distribution of source and receivers in the phase 6 MedSurg-ICU corridor simulation

In all phases, similar materials are applied to the boundary surfaces of the two wards. The absorption and scattering coefficients of the surface materials are shown in Table 7.1. In each phase, the same analysis is repeated for two different types of ceiling tiles: absorption coefficient = 0.1 and absorption coefficient = 0.3. This is necessary to test how different material applications affect the impact of floor-plate design on reverberant qualities of the corridors.

Table 7.1 Absorption coefficients of materials applied to the surfaces of the two wards

Surface	**Material**	**250Hz**	**500Hz**	**1kHz**	**2kHz**	**4kHz**	**SC**
Wall	Drywall	0.08	0.05	0.04	0.03	0.03	30%
Ceiling	Tile ($\alpha = 0.3$)	0.3	0.3	0.3	0.3	0.3	20%
Ceiling	Tile ($\alpha = 0.3$)	0.1	0.1	0.1	0.1	0.1	20%
Floor	Vinyl	0.02	0.03	0.03	0.03	0.02	10%

7.3 FINDINGS

Impulse response measurements

The averaged measured reverberation times in different corridors of each unit are shown in Figure 7.15. In the MedSurg-ICU, averaged reverberation times range between 0.44s and 0.56s across frequency. In one of the corridors reverberation times are as low as 0.30s and the highest was 0.76 s. In the Neuro-ICU corridors, averaged reverberation times are consistently higher compared to averaged reverberation times in the MedSurg-ICU (Figure 7.15), even though the Neuro-ICU is installed with absorptive acoustic ceiling tiles. The reverberation times in the Neuro-ICU range between 0.70 s and 0.87 s. The lowest reverberation time recorded in the Neuro-ICU corridors is 0.67 s and the highest was 0.92 s. The difference between the reverberation times measured in two ward corridors range between 33% and 68%. This result indicates the potential significant impact of corridor design in addition to absorptive surface material applications on the reverberation time. For example, the floor-plate design of the MedSurg-ICU corridor is more compact with shorter corridors. According to the previous Chapter 6 findings, in the corridor settings with more compact and shorter corridors, reverberation times are likely to be less.

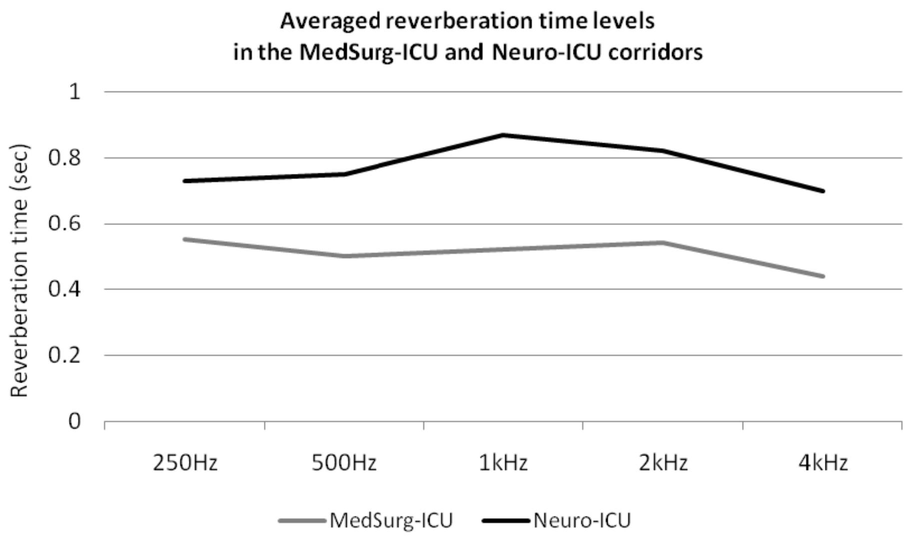


Figure 7.15 Averaged measured reverberation times in the MedSurg-ICU and Neuro-ICU corridors

Table 7.2 Just noticeable difference results of measured reverberation times in the two wards

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND (impulse response measurement)	33%	50%	68%	55%	62%

Acoustic Simulation Analysis

Simulation Phase 1: impact of corridor intersection type on RT30

According to the averaged simulation results, reverberation time is perceptibly higher at the T-shaped corridor intersection compared to the “+” shaped corridor intersection particularly at 250Hz, 500Hz, 1kHz and 2kHz (Figure 7.16 and Figure 7.17). In the light of the Chapter 6 findings, this result is expected because compared to a T-shaped corridor a cross shaped corridor has more branching corridors. In Chapter 6, increased *number of branches* is found to be significantly positively and negatively correlated with the reverberation time.

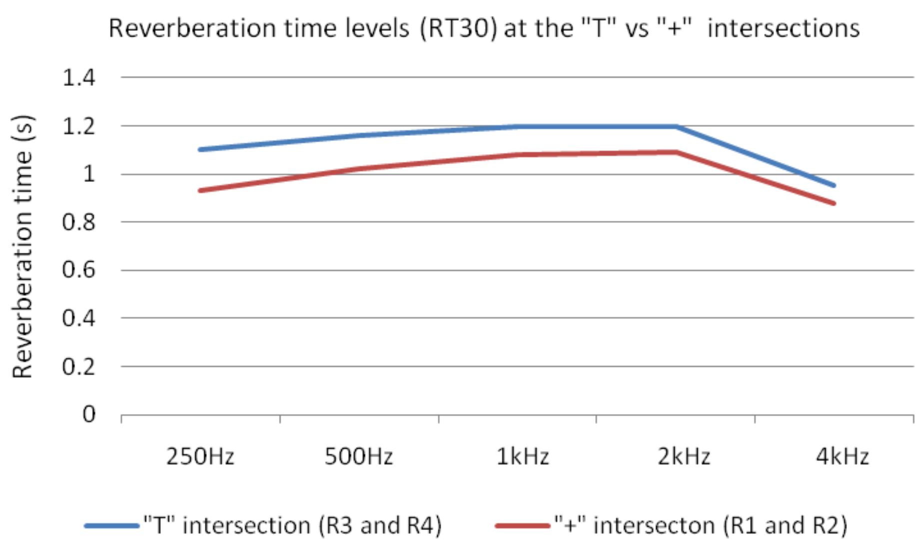


Figure 7.16 Averaged simulated reverberation times at the phase 1 “T” and “+”shaped intersections (ceiling tile $\alpha = 0.3$)

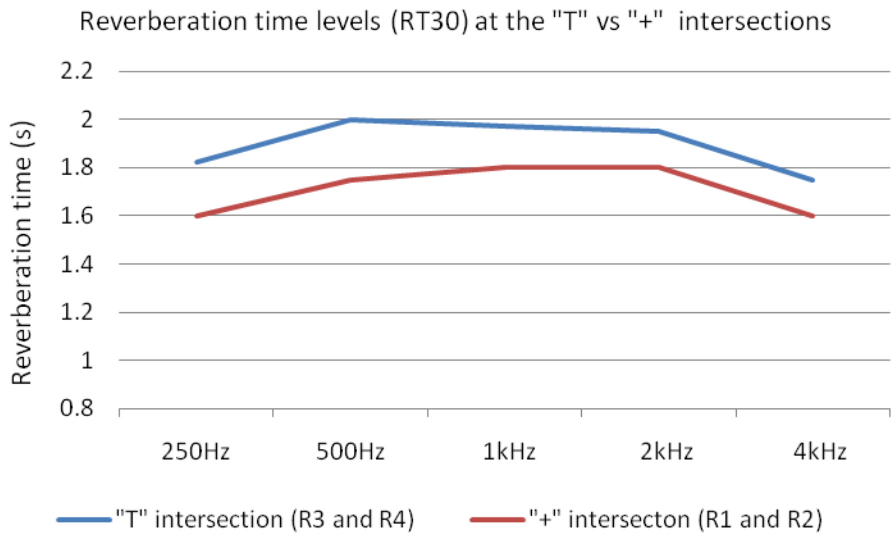


Figure 7.17 Averaged simulated reverberation times at the phase 1 “T” and “+”shaped intersections (ceiling tile α = 0.1)

Table 7.3 JND results of simulated reverberation times at the phase 1 “T” and “+”shaped intersections

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile α = 0.3	12%	13%	10%	10%	8%
JND ceiling tile α = 0.1	14%	15%	9%	8%	9%

Simulation phase 2: impact of branch number on RT30

In the Neuro-ICU corridor with multiple branches, averaged reverberation times are lower compared to the reverberation times in the MedSurg-ICU corridor without any branches. Similar to the phase 1 previous analysis, the difference is not as significant at high frequencies compared to the difference at lower frequencies including 250Hz, 500Hz and 1kHz (Figure 7.18 and Figure 7.19). This result is expected because in Chapter 6, increased number of branches is found to be significantly and negatively correlated with the reverberation time.

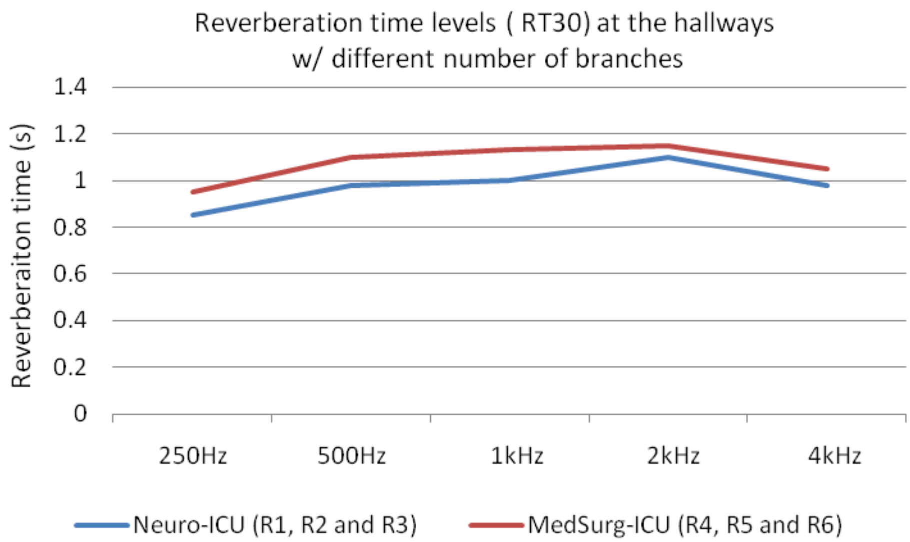


Figure 7.18 Averaged simulated reverberation times at the phase 2 corridors with different number of branches (ceiling tile $\alpha = 0.3$)

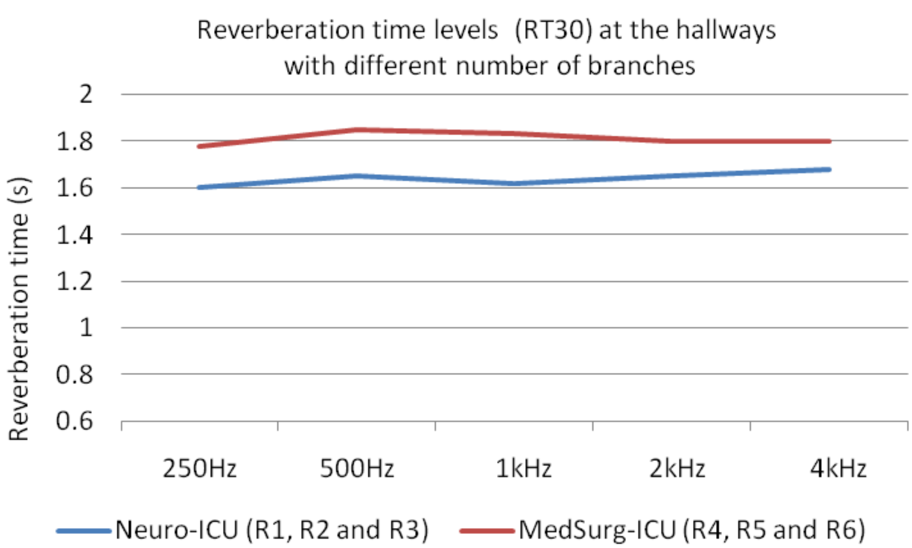


Figure 7.19 Averaged simulated reverberation times at the corridors with different number of branches (ceiling tile $\alpha = 0.1$)

Table 7.4 Just noticeable difference results of simulated reverberation times at the corridors with different number of branches

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile ($\alpha = 0.3$)	10%	12%	11%	4%	7%
JND ceiling tile ($\alpha = 0.1$)	11%	13%	13%	9%	7%

Simulation phase 3: impact of number of turns on RT30 levels

The averaged reverberation times are higher in the corridor that is 2 turns away from the sound source (Neuro-ICU) compared to the reverberation times in the corridor that is 1 turn away from the source (MedSurg-ICU). The difference is higher at lower frequencies including 250Hz, 500Hz and 1kHz (Figure 7.20 and Figure 7.21). This result is expected because in Chapter 6, increased *number of turns* is found to be significantly and positively correlated with reverberation time. However it is also possible that slightly larger volume of Neuro-ICU might be contributing to the larger RT30.

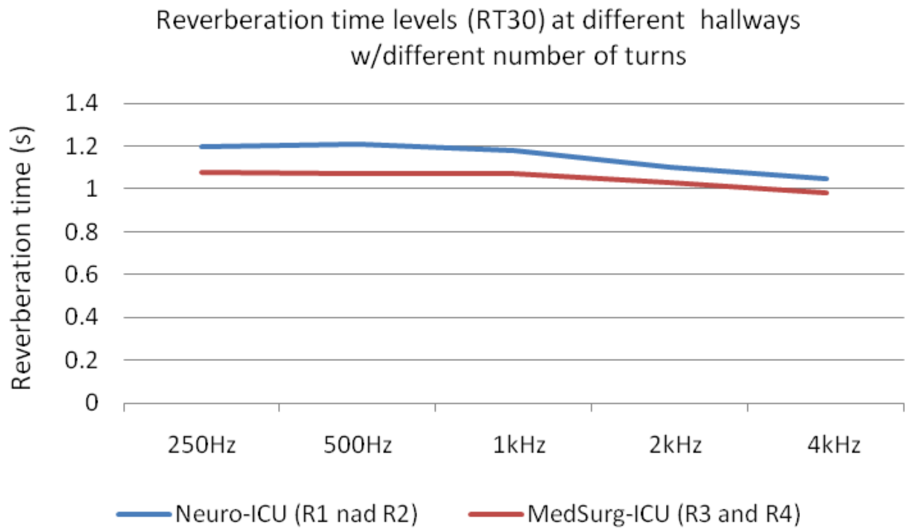


Figure 7.20 Averaged simulated reverberation times at the phase 3corridors that are 1 turn and 2 turns away from the source (ceiling tile $\alpha = 0.3$)

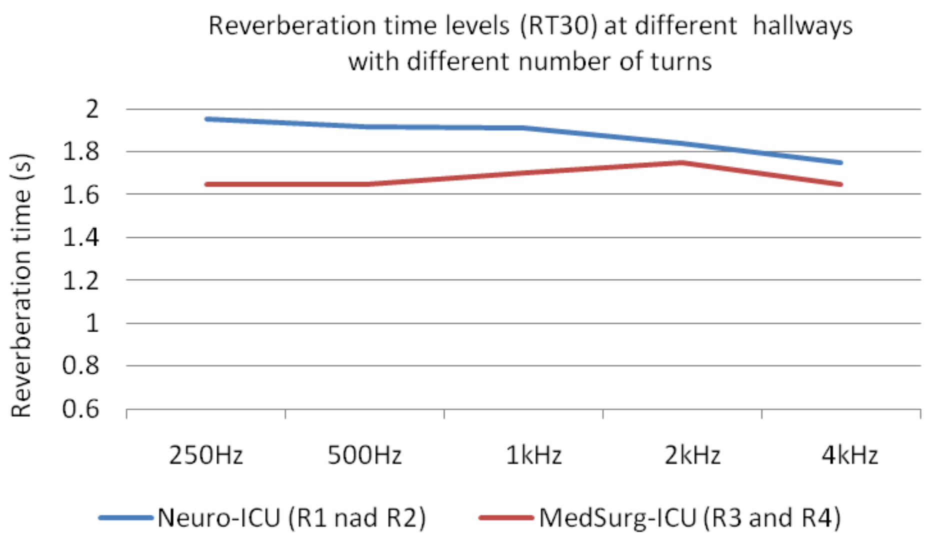


Figure 7.21 Averaged simulated reverberation times at the phase 3 corridors that are 1 turn and 2 turns away from the source (ceiling tile $\alpha = 0.1$)

Table 7.5 Just noticeable difference results of simulated reverberation times at the phase 3 corridors that are 1 and 2 turns away from the sound source

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile ($\alpha = 0.3$)	11%	13%	10%	6%	7%
JND ceiling tile ($\alpha = 0.1$)	18%	16%	12%	5%	6%

Simulation phase 4: impact of hallway length on RT30

The averaged reverberation time is longer in the longer corridor of the Neuro-ICU compared to the averaged reverberation time in the shorter corridor of the MedSurg-ICU. In particular, the difference is higher at lower frequencies including 250Hz, 500Hz and 1 kHz (Figure 7.22 and Figure 7.23). This result is expected because in Chapter 6, increased *corridor length* is found to be significantly and positively correlated with the reverberation time. However it is also possible that slightly larger volume of Neuro-ICU might be contributing to the larger RT30.

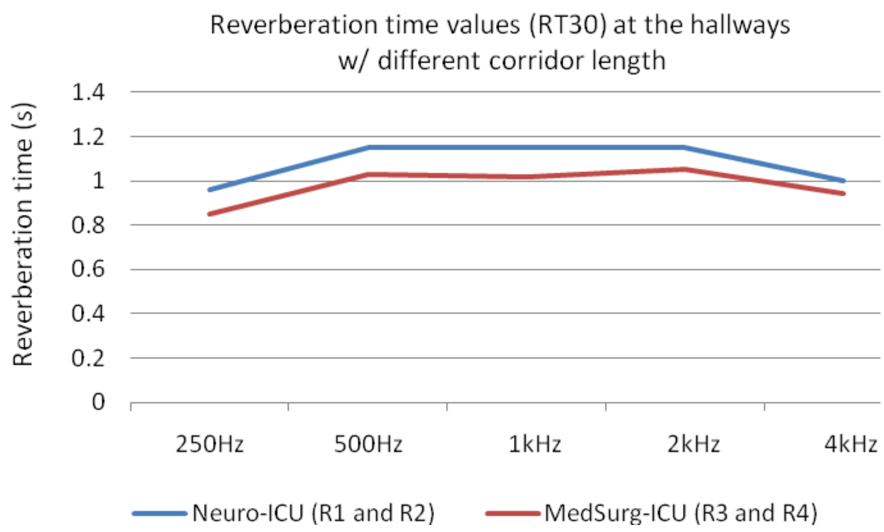


Figure 7.22 Averaged reverberation times in the phase 4 corridors with different corridor length (ceiling tile $\alpha = 0.3$)

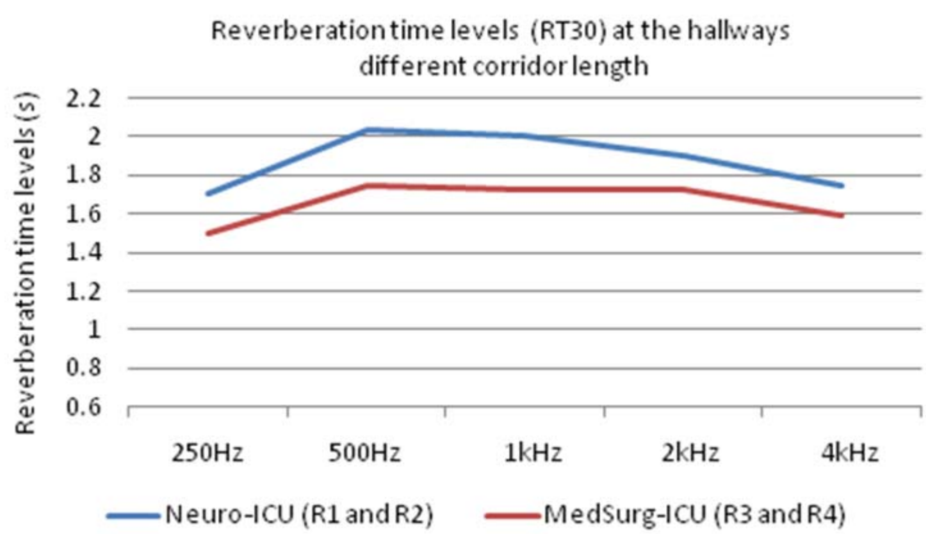


Figure 7.23 Averaged reverberation times in the phase 4 corridors with different corridor length (ceiling tile $\alpha = 0.1$)

Table 7.6 Just noticeable difference results of simulated reverberation times at the phase 4corridors with different corridor length

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile $\alpha = 0.3$	12%	11%	13%	9%	6%
JND ceiling tile $\alpha = 0.1$	13%	16%	15%	9%	10%

Simulation phase 5: impact of overall floor-plate shape on RT30

Even though, the Neuro-ICU has a more fragmented floor plate shape, the mean of the reverberation times both measured and predicted in different corridors of the Neuro-ICU are higher compared to the MedSurg-ICU. The relative grid distance values of the two unit floor-plate shapes are similar. On the other hand, the total corridor length of the Neuro-ICU is longer. Given these results, it is plausible to conclude the potential significant impact of total corridor length on the mean RT30 of the two unit corridors. Consistent with previous analysis, the difference is higher at lower frequencies including 250Hz, 500Hz and 1 kHz (Figure 7.24 and Figure 7.25).

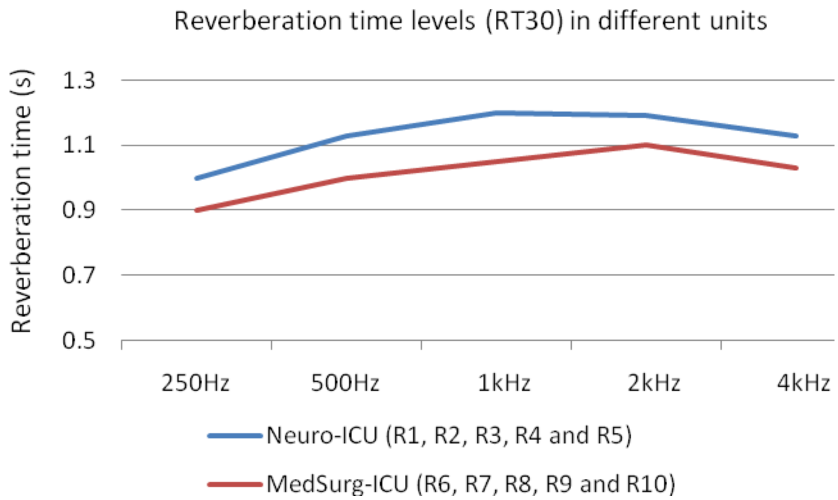


Figure 7.24 Averaged simulated reverberation times in the phase 5 corridors with different total corridor length (ceiling tile $\alpha = 0.3$)

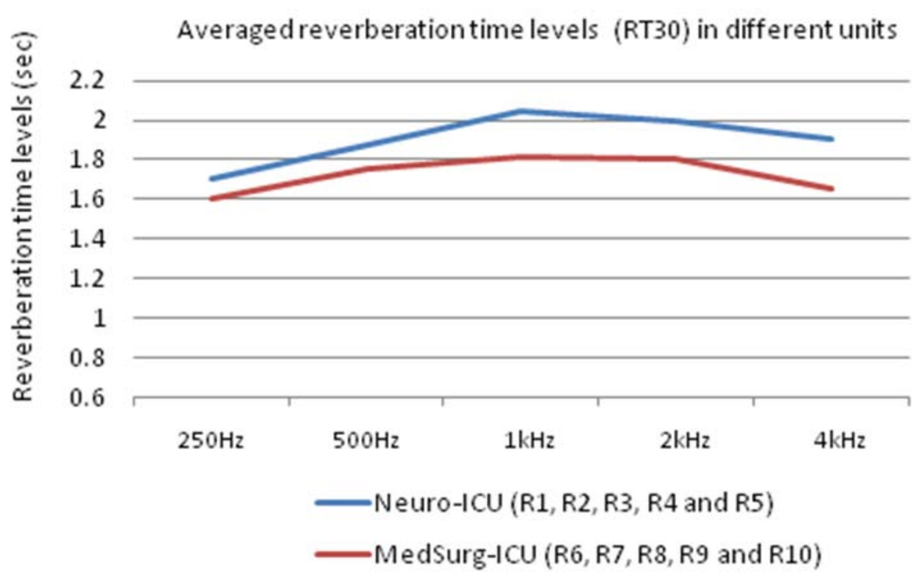


Figure 7.25 Averaged simulated reverberation times in the phase 5 corridors with different total corridor length (ceiling tile $\alpha = 0.1$)

Table 7.7 Just noticeable difference results of simulated reverberation times at the phase 5 corridors of two wards with different total corridor length

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile ($\alpha = 0.3$)	11%	13%	14%	7%	9%
JND ceiling tile ($\alpha = 0.1$)	15%	18%	17%	8%	6%

Simulation phase 6: impact of overall floor-plate shape on RT30 levels

Different from previous analysis, the mean of the predicted reverberation time in the idealized corridors of the Neuro-ICU is shorter compared to the mean reverberation times measured in the MedSurg-ICU corridors. In particular the difference is greater at low frequencies including 250Hz, 500Hz and 1 kHz (Figure 7.26 and Figure 7.27). These results can be expected based on the statistically significant relationships (found in Chapter 6) between floor-plate shape qualities and mean RT30. Idealized floor-plate shape of the Neuro-ICU is more fragmented and less elongated compared to the original floor-plate shape of the MedSurg-ICU. According to Chapter 6 findings, in more fragmented and less elongated floor-plates, mean RT30 is expected to be less.

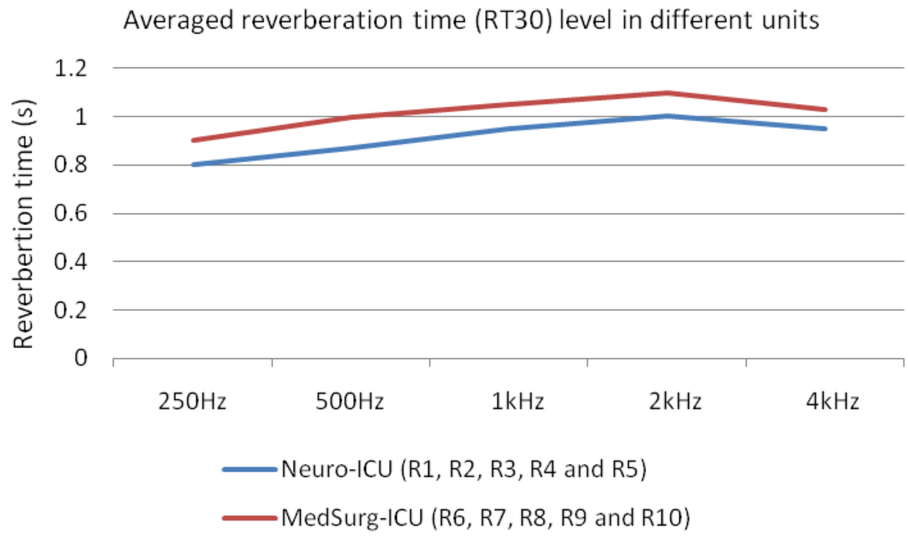


Figure 7.26 Averaged simulated reverberation times in the phase 6 corridors with similar length and different shape (ceiling tile $\alpha = 0.3$)

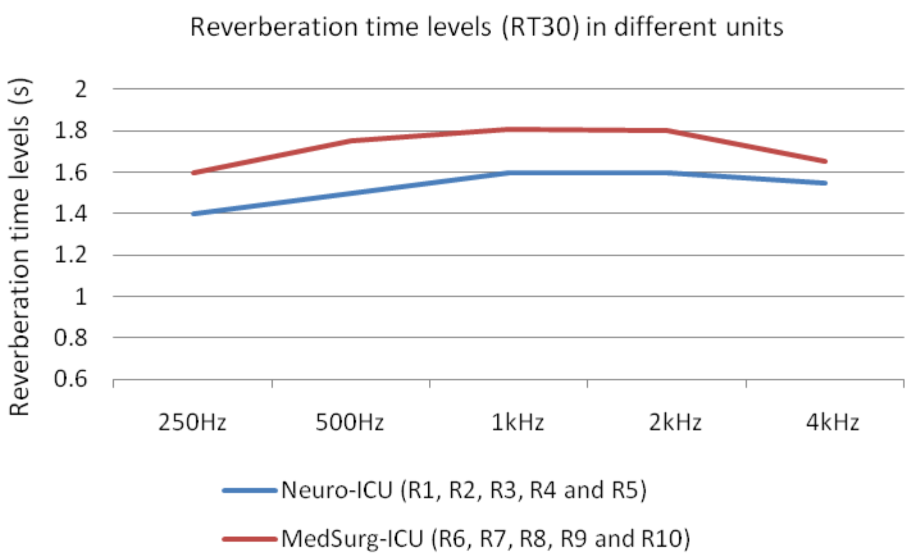


Figure 7.27 Averaged simulated reverberation times in the phase 6 corridors with similar length and different shape (ceiling tile $\alpha = 0.1$)

Table 7.8 Just noticeable difference results of simulated reverberation times at the phase 6 corridors of two wards with similar total corridor length

	250Hz	**500Hz**	**1kHz**	**2kHz**	**4kHz**
JND ceiling tile ($\alpha = 0.3$)	12%	14%	10%	9%	8%
JND ceiling tile ($\alpha = 0.1$)	14%	17%	13%	12%	6%

7.4 DISCUSSION

To assess the findings of previous theoretical studies conducted in Chapter 6, acoustic qualities of two real world hospital ward corridors are analyzed in Chapter 7 by conducting impulse response measurements (in situ measurements) and simulation studies.

Interestingly, even though the Neuro-ICU is installed with absorptive ceiling tiles, averaged RT30 is consistently and perceptibly higher in the Neuro-ICU compared to MedSurg-ICU. This suggests the potential significant impact of design features on RT30 in addition to absorptive qualities of surface materials. For example the MedSurg-ICU has a more compact layout with shorter corridors and thus a shorter reverberation time.

Simulation analysis is conducted in 6 phases. In each phase, the impact of particular corridor design features on RT30 levels is tested including *corridor length, number of* *branches, number of turns* and *overall design* (race track vs. tree-like design) by comparing predicted reverberation times in two wards.

Overall, the differences between the simulated averaged reverberation times measured in different corridors of the two wards are higher at lower frequencies including 250Hz, 500Hz and 1 kHz. At all times, the simulation study findings agree with the findings of Chapter 6. For example, the means of the predicted reverberation times in the corridors with *longer corridor length*, lower *number of branches* and higher *number of turns* from the sound source are higher. However, it is possible that slightly larger volume of Neuro-ICU might also be contributing to the larger RT30. In addition, (given two simulated unit corridors have similar total corridor length, width and height, and equal absorption treatment were applied), averaged reverberation times are higher in the more race track design unit (MedSurg-ICU) compared to the more fragmented and more compact idealized Neuro-ICU corridors. On the other hand, (when original designs of the two unit corridors were considered), increased *corridor length* in the Neuro-ICU led to significant increase in the reverberation times.

To summarize in the units with shorter, more compact, fragmented corridors with multiple number of branching hallways, reverberation time levels are likely to be less. Moreover higher number of turns also potentially increases reverberation time.

CHAPTER 8

CONCLUSION

8.1 SUMMARY of FINDINGS

Chapter 1

In Chapter 1, introductory information about the general structure of the thesis and the goals of the study are provided.

Chapter 2

By conducting three empirical studies, Chapter 2 documented the objective and subjective qualities of the hospital sound environments with different architectural designs, assessed the effectiveness of newer acoustic metrics in capturing caregiver perceptions, and evaluated the impact of particular noise sources on caregiver outcomes. In total, three different empirical studies have been conducted. These studies took place in two 20-bed ICUs: a new Neurological-ICU and a 1980s-era Medical-Surgical-ICU.

Empirical study 1 assessed the objective and subjective noise levels at different locations in the two ICUs. The MedSurg-ICU is perceived as louder, more annoying, and having a greater negative impact of noise on work performance, health outcomes, and anxiety as compared to the Neuro-ICU. Surprisingly, there is little difference between two ICU sound environments using traditional overall noise measures. The objective differences between the occupied sound environments in the two units emerged more clearly through a more comprehensive analysis of the “occurrence rate” of peak and maximum levels, frequency content, and the speech interference level. Furthermore, mid-level transient sound occurrence rates are significantly and positively correlated to perceived annoyance and loudness levels.

Empirical study 2 documented the objective and subjective noise levels during different times at each unit nurse stations by conducting the occurrence rate analysis and assessing nurse perceptions. Sound environments of the two unit nurse stations are significantly different based on the occurrence rate analysis. This is consistent with nurse perceptions. The MedSurg-ICU is consistently perceived as more annoying and louder during different times of the day and days of the week. Similar to the previous empirical study findings, these two sound environments are similar based on traditional Leq noise level analysis.

Empirical study 3 compared the level of nurse disturbance due to overall-noise and alarms in the two ICUs. MedSurg-ICU nurses have perceived medical alarms as more detrimental to their work performance and health outcomes, anxiety and annoyance levels compared to Neuro-ICU nurses. Interestingly, alarms are perceived to be as disturbing as overall-noise by nurses in both units.

Overall, chapter 2 findings suggest that in particular impulsive characteristics of healthcare sound environments potentially lead to negative health, wellbeing and performance outcomes among caregivers. Moreover the use of more detailed acoustic metrics such as occurrence rate (a newer metric used in this study) can provide a better picture than traditional measures of the aspects of the hospital sound environments as they impact user experience and well being. Moreover, objective and subjective qualities of hospital sound environments can vary between settings with different designs. However conducting more controlled studies are necessary to identify the impact of particular design features on the acoustic qualities of healthcare settings.

Chapter 3

By reviewing literature and conducting an empirical study, Chapter 3 provided a comprehensive overview of factors related to auditory monitoring. Additionally, results from a case study comparing nurses` auditory monitoring performance in two ICUs with different architectural designs are presented.

The literature review findings indicate that different factors can affect the monitoring of auditory cues including environmental factors and acoustic qualities of signals. For example, in highly reverberant and noisy spaces, localization and detection of auditory cues can be very challenging. In reverberant spaces, late arriving reflections can diminish the positive effects of early reflections. In spaces with high background noise levels, the signal-to-noise ratio decreases and therefore the signal becomes less distinguishable.

As a part of the empirical study, nurses are asked to rate the importance of different nurse tasks and different types of including auditory cues for patient safety. The ICU nurses in both units have indicated that auditory monitoring is as highly important and similar in importance to visual monitoring for patient safety. Moreover, a majority of the nurses have found various medical alarms highly important for patient safety such as ventilator alarms, patient monitor alarms, IV pump alarm, and nurse call as well as ventilator hissing sound. The nurses also indicated that they monitor these critical sounds at multiple different locations in their units. These key listening locations include: patient rooms, nurse stations, corridors in both wards and the medication preparation zone in the Neuro-ICU.

Nurses in the two units are also asked to rate their ability to conduct sound tasks in their units. In the MedSurg-ICU, nurse hearing and localization performance are perceived to be higher compared to the Neuro-ICU even though the Neuro-ICU included a high performance absorptive acoustic ceiling. Acoustic ceiling tiles are commonly used to decrease noise levels and reverberation times. Similarly, in MedSurg-ICU averaged reverberation times are perceptibly shorter compared to Neuro-ICU. This finding indicates the potential significant impact of other design features such as volume and corridor length on reverberant qualities of hospital sound environments in addition to absorption qualities of surface materials.

Overall, chapter 3 findings suggest that like visual monitoring, auditory monitoring is a highly critical nurse task for patient safety. Nurses monitor a variety of different critical sounds including alarm and non-alarm sounds at different locations in the nursing units. Nurses` auditory monitoring performance can vary in healthcare settings with different reverberant qualities. The design of hospitals is complex and different design features might contribute to reverberant qualities of hospital sound environments. Therefore, conducting more controlled studies is necessary to identify design features impacting reverberant qualities of hospital sound environments.

Chapter 4

By reviewing previous literature, Chapter 4 had provided an overview of room-acoustics parameters, the sound behavior in proportional and non-proportional spaces, and the association between floor-plate design and acoustics.

Reverberation time has been commonly used for the acoustic analysis of different types of spaces including long spaces and rooms. Newer room acoustic-parameters including early decay time, clarity and sound strength have been developed particularly for the acoustic analysis of concert halls (a proportional space). However, applicability of these newer acoustic parameters to other spaces has not yet been resolved.

Related with their design qualities such as spatial proportions, the acoustic characteristics of sound environments can vary significantly. Therefore acoustic theories applicable in one type of space might not be applicable to another space. Various studies have been conducted in concert halls and statistically analyzed the relationship between specific design characteristics of floor-plate shapes such as width, length and acoustic outcomes. However, the number of studies that systematically and statistically analyzed the relationship between design and acoustics of long enclosures still remains limited. Some studies explored the acoustics of long enclosures with complex floor-plate geometries such as underground stations with branches or staggered urban streets. However, not many studies investigated the acoustic conditions of inter-connected corridors located in the buildings.

Overall, the study findings indicate that as the shape of the long enclosures gets more complicated, sound behavior in these settings also becomes highly complicated. This research conducted more controlled follow-up studies to clarify the impact of specific design features on the acoustics of inter-connected corridors with complex floor-plate shapes.

Chapter 5

Chapter 5 has conducted various impulse response measurements and acoustic simulation analysis to assess the effectiveness of acoustic modeling tools in estimating acoustic qualities of non-proportional spaces.

Impulse response measurements (in situ measurements) have been commonly used for the assessment of reverberant qualities of architectural settings including proportional and non-proportional spaces. Acoustic simulation programs have been particularly used for estimating the acoustic qualities of proportional spaces (rooms) such as concert halls. Various validation studies have tested the reliability of these results predicted by the acoustic modeling programs. In particular, the effectiveness of hybrid prediction methods has been validated. However, not many studies have tested the effectiveness of prediction methods in estimating the acoustics of long enclosures. This study has conducted various impulse response measurements and acoustic simulation analyses in long enclosures with different floor-plate shapes to compare the difference between field measured and predicted results. Most times predicted results are within 5-22% accuracy with a few exceptions. This is parallel with the finding of previous studies. For example, in Kang`s (2002b) study the difference between predicted and measured results range between 10-25%. He has also used the same simulation program to conduct theoretical studies and explore the relationship between design and acoustics of long enclosures.

Another analysis has been conducted to compare the behavior of sound in a T-shaped corridor and a single corridor. Different from single corridor, the trend of the data sets recorded in the T-shaped corridor is not linear. In particular, the shape of the data set trend lines in the non-visual sound field of the T-shaped corridor is more complex compared to that in the visual sound field. This can be explained with the dominant effects of the reflections in the non-visual sound field.

Overall, the findings of Chapter 5 suggest the potential effectiveness of an acoustic simulation tool with hybrid prediction (i.e., CATT) in studying the acoustic qualities of complex hospital sound environments.

Chapter 6

Chapter 6 presents the results of a heuristic design analysis, and statistically explores the association between acoustics and design variables of interconnected corridors.

First, a pilot study is conducted in the inter-connected corridors of educational settings. The pilot study findings suggest the potential significant impact of design features of particular hallways (e.g., number of turns, corridor length, and number of branches) on reverberation time values. For example, according to findings of the study, in the hallways that are 2 turns away from the sound source, averaged reverberation time values are likely to be higher compared to hallways 1 turn away from the sound source. Moreover in the longer corridors, averaged reverberation time values are likely to be higher compared to shorter corridors. On the other hand, in the hallways with higher number branches, the reverberation time values are expected be lower compared to hallways with lower number of branches.

To test the findings of the pilot study, a more controlled follow up study (Empirical Study 1) is conducted by using the CATT acoustic simulation program. Various theoretical design models are generated based on the findings of the heuristic design analysis. According to the findings, the *corridor length* of the hallways located in the non-visual sound fields is significantly and positively correlated with averaged reverberation time values. In constrast, the *number of branches* variable is significantlyand negatively correlated with reverberation time values.

Another theoretical design analysis (Empirical Study 2) is conducted to assess the effects of overall floor-plate shape characteristics of inter-connected corridor systems on averaged reverberation time values. According to this analysis, RGD is positively correlated with averaged reverberation time values and VF is negatively correlated with mean reverberation time values. Overall these findings agree with the Empirical Study 1 findings as higher RGD values indicate more elongated floor-plates with potentially longer corridors. On the other hand, more fragmented floor-plates with higher VF values are likely to have shorter corridors.

Overall, the findings of Chapter 6 suggest that in addition of design features of particular hallways such as corridor length, number of turns and number of branching hallways, overall design of nursing unit floor-plate shapes can have significant impact on the reverberant qualities of hospital sound environments To provide less reverberant sound environments, designers should consider more compact and more fragmented nursing unit floor-plate shapes.. All else equal, nursing units with shorter corridors and with more branching hallways have shorter reverberation times. Also, the more turns that care providers are from the patient rooms, the poorer their ability to monitor critical sounds originated in the patient rooms.

Chapter 7

In Chapter 7, the validity of the previous study findings (in Chapter 6) has been assessed by analyzing the acoustics of real-world hospital ward corridors via impulse response measurements and acoustic simulation analysis.

The impulse response measurements are conducted in different corridors of the two ICUs already mentioned. In the Neuro-ICU averaged RT30 levels are consistently and perceptibly higher compared to averaged RT30 in the MedSurg-ICU corridors. This suggested the significant impact of different design features in addition to absorptive qualities of the surface materials. For example, the MedSurg-ICU has a more compact corridor layout with shorter corridors and thus a shorter reverberation time.

Simulation analysis is conducted in 6 phases. In each phase, the impact of a particular corridor design feature on RT30 is assessed. At all times, the simulation study findings have agreed with the findings of Chapter 6. For example, the mean of the reverberation times measured/predicted in the corridors with longer *corridor length*, lower *number of branches* and higher *numbers of turns* from the sound source are higher. Averaged reverberation times are also lower in the more fragmented and more compact unit (Neuro-ICU) compared to less fragmented and less compact (MedSurg-ICU) when both the simulated units has similar total corridor length, width and height and equal absorption treatments. On the other hand, increased *total corridor length* in the Neuro-ICU led to significant increase in the reverberation times.

Overall, Chapter 7 findings confirm the findings of Chapter 6. In other words, when designing real world hospital floor-plate geometries, designers can refer to the findings of theoretical study findings presented in Chapter 6.

8.2 CONTRIBUTION

The research findings contribute to ongoing efforts to improve the currently problematic hospital sound environments in different ways. This research:

- Provides a detailed understanding of the hospital sound environments by studying noise propagation and architectural acoustics
- Diagnoses problematic aspects of hospital sound environments that particularly relate to caregiver outcomes including performance and wellbeing
- Proposes and validates a newer acoustic metric effective in capturing unique qualities of hospital sound environments
- Tests and validates the effectiveness of more detailed acoustic metrics (compared to traditional metrics) that have not been commonly used in noise propagation analysis in the hospitals
- Provides a detailed understanding of patient auditory monitoring particularly conducted in the ICUs
- Provides a multi-disciplinary study framework that links three different types of variables including design, acoustics and occupant outcomes
- Expands the relationship between design and acoustics by conducting statistical analysis
- Clarifies design features of long enclosures affecting sound environments and floor-plate design qualities of nursing unit corridors conductive of critical sound tasks
- Expands the limited knowledge on acoustics of long enclosures by examining acoustics of interconnected corridors
- Suggests the use of hybrid acoustic simulation programs for the analysis of hospital sound environments and long enclosures in particular interconnected corridors

- Provides an opportunity for designers, engineers and care providers to think and discuss hospital sound environments starting from the early design phases by linking design and acoustics
- Defines a new area where sound localization research is applicable

8.3 LIMITATIONS

Limitations

External validity

- The studies introduced in Chapter 1 and 2 are conducted in the ICUs and the study participants are ICU nurses. Related with the sample group characteristics, generalizability of the Chapter 1 and 2 findings are limited to ICUs.
- In Chapter 6, acoustic simulation study has considered theoretical design models generated based on the heuristic design analysis of the nursing units. Related with the limited size of the sample group, the generalizability of the Chapter 6 findings are limited to nursing units.
- In Chapter 6, the floor-plate design qualities of corridor settings are correlated with reverberant qualities of hospital sound environments. The floor-plate shape analysis program and floor-plate shape metrics used in Chapter 6 are only effective in quantifying the shapes of the tree-like design nursing unit corridors with limited complexity. Due to the limited size of the sample group, the findings of this analysis are only generalizable to tree-like design corridors.

8.4 FUTURE WORK

Hospitals have complex and problematic sound environments. This research was able to address particular problems of the hospital sound environments by statistically assessing the relationship between architectural design features, acoustics and caregiver outcomes. Future work should also consider patient and visitor outcomes. In addition, this study focused on self-reported outcomes. While they present challenges in access and measurement future work might explore other safety, quality and well-being outcomes such as communication errors, medication errors and physiological stress.

Moreover, this research focused particularly on reverberant and sound level qualities of hospital sound environments. Even though reverberation time has significant impact on speech intelligibility levels, this research did not focus on the direct relationship between speech intelligibility and design features. In fact, speech intelligibility was one of acoustic metrics that was not reliably predicted by CATT Acoustics V8 for the complex long enclosures modeled. Therefore, future research should also explore reliable acoustic measurement/prediction methods for the study of speech intelligibility in hospitals. Also, the design and acoustics of nursing units was the focus of this study. Future research should also analyze acoustics and design features of different healthcare settings such as emergency departments.

APPENDIX A: DEFINITION OF TERMS

The following definitions of the acoustics terms are gathered from the following sources: Mehta (1997); Long (2006); and Everest, and Pohlmann (2009).

Absorption coefficient: A measure of the sound absorbing property of a surface. More specifically, absorption coefficient is defined as the fraction of the incident sound energy absorbed by a surface.

Artificial/dummy head: A binaural acoustic measuring system consisting of two microphones built into the ears of an artificial human head and torso.

Occurrence rate: Percentage of the time that specified peak and maximum sound levels exceed certain sound pressure levels.

***A-weighting*:** A means of electronically simulating the unequal sensitivity of the human ear at various frequencies by filtering.

Binaural hearing: A recording and playback configuration emulating hearing with two ears.

Centre time (Ts): Center time is a measure used to describe where the sound energy is concentrated in the echogram (energy distribution map of the sound). Low values of Ts indicate that the arriving sound is concentrated in the early part while high values indicate early reflections are weak or decay is slow.

C-weighting: An attempt to electronically reduce the unequal sensitivity of the human ear at various frequencies by filtering. C-weighting is similar to A-weighting except that C-weighting is more applicable to loud sounds and low frequency sounds.

Clarity (C): Clarity is a measure used to quantify the ability to distinguish individual sounds (e.g., music, warning, whirring machine) from the general audible stream, or the degree to which rapidly occurring individual sounds are distinguishable. Clarity values depend on the sound level difference between early and late arriving reverberant energy. Direct sound and early reflections are usually considered to be useful sounds that improve clarity. The cutoff value that represents the transition from early to late sound is typically considered to be 80ms for music and 50ms for speech.

Cocktail party effect: Humans ability to focus one`s listening attention on a single talker among a mixture of conversations and background noises.

Critical distance: The distance at which the sound pressure level of the direct and reverberant sound fields are equal.

Decibel: The decibel is a logarithmic unit that indicates the ratio of a physical quantity relative to a specified or implied reference level. It is widely known as a measure of sound pressure level.

Definition (D): Definition can be a measure of speech intelligibility. Definition values depend on the percentage ratio of the early arriving sound energy to total sound energy. Direct sound and early reflections are considered to be useful sounds that improve definition. The cutoff value that represents the transition from early to late sound is considered to be 50ms for speech.

Diffraction: A change in the direction of propagation of sound as a result of bending caused by a barrier in the path of the sound wave.

Diffuse field: A sound field in which the sound comes in equal intensity from all directions. For example, a diffuse sound field can be obtained in a large room with highly reflective surfaces.

Diffuse reflection: Reflection of sound from a rough surface in such a manner that the sound rays will diffuse in many different directions.

Direct sound: The sound that arrives at a receiver along a direct line from the source without reflection from any surface.

Early decay time (EDT): Early decay time is another acoustic measure used to quantify sound decay. EDT is the time required for the initial part the sound to decay 10dB. This value is multiplied by 6 to extrapolate the results to RT60. Main difference between two measures is that EDT is composed of a few early reflections while RT consists of multitude reflections. This is mainly because EDT is calculated from the initial slope of the reverberation curve.

Exceedance level: Level of sound exceeded during specified percent of the time. For example, L_{33} = 50 would mean that 33%of the run time, the decibel level was greater than or equal to 50dB.

Equivalent sound pressure level: The sound pressure level of a steady sound which, in a specific time period, has the same energy as the time varying sound.

Frequency: The number of cycles per second measured. The unit of frequency is cycles per second which is called Hertz (Hz).

Heuristic design analysis: Obtaining information through systematic evaluation.

Hybrid prediction method: A prediction method that optimizes the best features of two different acoustic prediction models: image source model (ISM) and ray tracing (RT).

Image source modeling: A prediction method that determines the images of the source to calculate the direction of the reflected sound rays off the enclosure surfaces.

Impulse response: Impulse response represents an acoustic "fingerprint" of a setting from which various key acoustic metrics can be derived.

Impulsive noise: A noise of short duration particularly of high intensity.

Inter-aural cross correlation: Correlating acoustic qualities of the signals received by the right and left ear**.**

Inter-aural level difference: Sound level difference between the sound signals reaching the right and left ear.

Inter-aural time difference: Difference between the arrival times of the sound signals reaching the right and left ear.

Intermittent sound: A sound which is discontinuous or fluctuates.

Just noticeable difference: Average minimal perceptible change in objective parameters.

Lateral energy fraction (LF/LFC): Lateral fraction is used to assess the relative contribution of strong early lateral reflections arriving at the listener from either side at the angles of 20-90degree relative to the front of the listener. Statistically, lateral fraction is the linear ratio of lateral energy or the energy arriving from the sides within (5ms-80ms) to total energy within (0ms-80ms).

Lateral fraction: Ratio of sound energy arriving laterally (from the side walls) over sound energy arriving from all directions.

Long enclosures: Enclosed settings with higher L/H; L/W ratio compared to normal rooms. (L: length; H: height; W: width).

Loudness: An auditory sensation. Loudness depends on factors such as sound pressure level, frequency of sound and duration.

Maximum sound pressure level: Maximum sound level is the highest sound pressure level reading of a conventional sound level meter in a specified time interval.

Minimum sound pressure level: Minimum sound level is the lowest sound pressure level reading of a conventional sound level meter in a specified time interval.

Moderator effect: A situation in which the direction or magnitude of the relationship between two variables depends on the value of one or more other variables.

Monaural hearing: Hearing auditory signals with one receptor (ears/microphone).

Noise: An unwanted sound.

Noise fluctuations: Time variant nature of the noise levels.

Noise-induced outcomes: Occupant outcomes associated with noise characteristics such as level.

Non-visual sound field: Sound field/zone that is not visible from the sound source.

Objective noise level: Noise levels quantified with the use of a sound level meter.

Octave band: Frequency interval between two sounds whose frequencies are related to each other in the ratio of 1:2.

Omni-directional source: A source that radiates sound in all directions equally.

One-third octave band: An octave band divided into three one-third octave bands. The upper frequency limit of a one-third octave band is $2^{1/3}$ times its lower frequency limit.

Peak sound pressure level: Peak sound pressure level is different from maximum sound pressure level. It represents the true peak of sound pressure wave. Therefore the signal does not pass through a pressure circuit or calculator. For a pure tone the Peak is 3dB above the Maximum sound level. However for varying signals this difference can be much higher.

Pink noise: A noise whose level decreases with increasing frequency in such a way that there is a constant energy in every octave.

Precedence effect: Early reflections arriving between 2ms and 50 ms after the arrival of the direct sound are typically considered to be useful reflections because they can be combined with the direct sound. The human auditory system localizes sound sources by considering early/first arriving sounds and this phenomenon is known as precedence effect.

Ray tracing: Prediction of numerical acoustic measures by tracing acoustic rays based on the rules of the geometric acoustics.

Relative grid distance: *Relative grid distance* (RGD) values represent the degree to which a floor-plate shape diverges from square.

Reverberant sound field: A sound field created by repeated reflections of sound from the boundaries in an enclosed space.

Reverberation: The continuation of sound in an enclosed space after the initial source has terminated.

Reverberation time *(RT60, RT30, RT15):* Reverberation time is a measure of sound decay. In scientific terms, reverberation time (RT60) is the time it takes sound to decay 60dB or to one millionth of its initial energy. When the background noise in a space is loud enough that a full 60dB decrease cannot be feasibly measured, reverberation time is also measured over a range of 30dB (RT30) and 15dB (RT15). In more general terms, reverberation time refers to the time it takes for sound to fade away after a source has stopped. Strong reflections provided by the enclosure extend the reverberation time. Excessive values of reverberation time can interfere with the activities conducted in the settings such as speech intelligibility and sound localization.

Room acoustics: Field of acoustics that defines the sound decay qualities in enclosed settings.

Room acoustics parameters: Measures used to define acoustic qualities of enclosed settings such as concert halls and lecture rooms.

Room gain or Sound strength (G): Sound strength is used to assess sound level gained by the room conditions. It represents "the total energy of an impulse response at a location in a room relative to the total energy of the same source measured in an anechoic chamber at a distance of 10m" (Chiang, 1994). Sound strength approximates the subjective sense of loudness.

Scattering: An irregular diffraction of sound in many directions.

Scattering coefficient: A parameter used in acoustic simulation programs to quantify diffusely reflective qualities of the boundary surfaces.

Signal to noise ratio (SNR): A measure of signal strength relative to background noise.

Soundscape: An environment of sound (sonic environment) with emphasis on the way it is perceived and understood by the occupants.

Sound lateralization: A type of sound localization but where the subjects localize the sounds in their heads as signals are introduced via head phones.

Sound level meter: An instrument for measuring sound pressure levels and other acoustic parameters.

Sound localization: A hearing system`s ability to make accurate judgments about the distance and direction of the sound source.

Sound pressure level: Sound pressure level is a logarithmic measure of the effective sound pressure of a sound relative to a reference value. The commonly used reference sound pressure in air is pref = 20 μPa (rms), which is usually considered as the threshold of human hearing.

Sound strength: The sound level gained by the room conditions.

Spectral content (frequency spectrum): Distribution of sound energy across different frequencies.

Specular reflection: Reflection of a sound from a smooth surface in such a manner that the angle of the incidence is equal to the angle of the reflection.

Speech intelligibility: Intelligibility of speech that is usually measured in the presence of noise and sometimes reverberation. Speech intelligibility is quantified in different ways such as the percentage of speech units understood correctly by a listener.

Speech interference levels: Arithmetic average of the sound pressure levels at 500Hz, 1kHz and 2kHz center frequencies and is a measure of the degree to which background noise interferes with speech.

Subjective noise level: Loudness levels reported by the occupants.

The center time (Ts): A measure used to describe where the sound energy is concentrated in the echogram.

Visual fragmentation: *Visual fragmentation* (VF) values reflect the convexity of a floor-plate shape defined as the amount of directional changes needed to connect any two locations on the floor-plate.

Visual sound field: Sound field/zone that is visible from the sound source.

White noise: A noise whose energy is uniform over a wide range of frequencies.

APPENDIX B: DESIGN QUALITIES OF THE NEURO-ICU AND MEDSURG-ICU

The Neurological ICU (Neuro-ICU) is a recently opened 20-bed unit (A.B1). This unit received the "ICU Design Citation" award in 2008, co-sponsored by the Society of Critical Care Medicine (SCCM), the American Association of Critical Care Nurses (AACN), and the American Institute of Architects Academy on Architecture for Health (AIA). The award was for the Neuro-ICU's design intent to enhance the critical care environment for patients, families and clinicians. Some unit design features include large private patient rooms with family studios and distributed nurse work areas and care support areas. High performance absorptive acoustic ceiling tiles and drop ceiling applications reside mainly along the two parallel sides of the corridors and at the nurse stations, painted dry wall, acoustic rubber flooring, and 1.8 m (6 ft) wide (two-wing) glass patient room doors are some of the surface applications in the unit. The patient care core of the Neuro-ICU sits on approximately 1,765 m^2 (19,000 sqft).

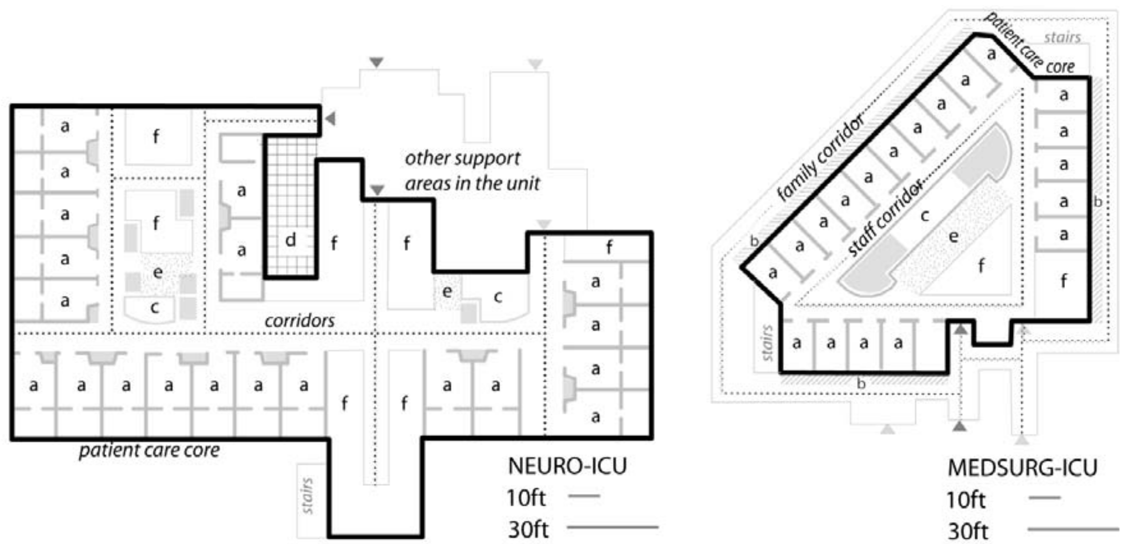


Figure A.B1 Floor-plans of two critical care units (Key=a: patient room with family studio, b: family area around the periphery of the unit, c: central nurse station, d: open space, e: MED. area (i.e., medication preparation, pixes machine), f: other service/support areas; grey highlighted zones: de-central nurse stations in the Neuro-ICU or patient observation cores in the MedSurg-ICU).

The Neuro-ICU has a *cluster*-type architectural layout, composed of a 6-bed and 14-bed clusters. Each cluster has a central nurse station with its own care support areas (e.g., medication room, supply room), and computerized patient monitoring system. In total, the unit has two central nurse stations and seventeen distributed nurse work areas. Each 36 m^2 (390 sqft) patient room is segregated into two portions: a patient care area (approximately two thirds of the total area) and a family lounge area. The two areas are separated by a semi-opaque glass wall. Approximately 1/3rd of the patient care core floor area is occupied by the corridors, which are 183 m (600 ft) total length. The Neuro-ICU includes additional spaces such as public family areas, CT scan lab, and a healing garden. The total area of the Neuro-ICU is approximately is 2,229 m^2 (24,000 sqft).

The Medical Surgical ICU (MedSurg-ICU) is a 1980s era 20-bed unit (Figure A.B1). Compared to the Neuro-ICU, the MedSurg-ICU has more traditional surface applications including standard ceiling tiles, vinyl flooring, approximately 1.5 m (5 ft) wide (two-wing) glass patient doors, and painted dry wall. The patient care core of this unit is approximately 817.5 m^2 (8,800 sqft).

The MedSurg-ICU has a triangular shape *race track* layout design. In this layout, medical and support areas are located in the center and patient rooms are located on the perimeter, with a corridor separating the two space types. Twenty private patient rooms are organized around one large triangular-shaped service core that contains a centralized nurse station and other care support areas such as medication room, equipment and supply room. The centralized nurse station contains two patient monitoring cores (each serves up to ten patients) at the corners and has a separate computerized patient monitoring system. Patient rooms in this unit are approximately 18 m^2 (190 sqft). This particular layout type requires the use of segregated corridors for staff and family members. Approximately 1/4th of the patient care core floor area is occupied by the staff corridor, with a total length of 73 m (240 ft). The total MedSurg-ICU sits on approximately 1161 m^2 (12,500 sqft).

Overall, floor-plate shape of the Neuro-ICU is more fragmented compared to MedSurg-ICU (VF=1, VF=0.8, respectively). On the other hand, floor-plate shapes of the two units are similarly elongated (RGD=2.2).

APPENDIX C: NOISE LEVEL FIELD MEASUREMENTS

Monaural recordings

Although the human auditory system gathers information with two ears (a.k.a. binaural hearing) some auditory information such as loudness can be obtained by listening through one ear (a.k.a. monaural hearing). Based on their practicality and convenience, usually sound level meters (with a single channel microphone such as a condenser microphone) are used for the assessment of background noise levels via monaural recordings. The condenser microphone samples the sounds as shown in Figure A.C1. The preamplifier prepares an electronic signal for further amplifications and processing. It also keeps the microphone away from the body of the instrument to avoid strong reflections. The body of the instrument includes electronic circuits to process the sound detected by the microphone. The digital signal processor filters the sound in various ways (e.g., A, C and Flat broadband filters; Real-time FFT and 1/1 and 1/3 octave band filters; Slow, Fast RMS detectors; Impulse and Peak detectors) and prepares the readouts to be displayed on the digital LCD display of the instrument or exported to a computer.

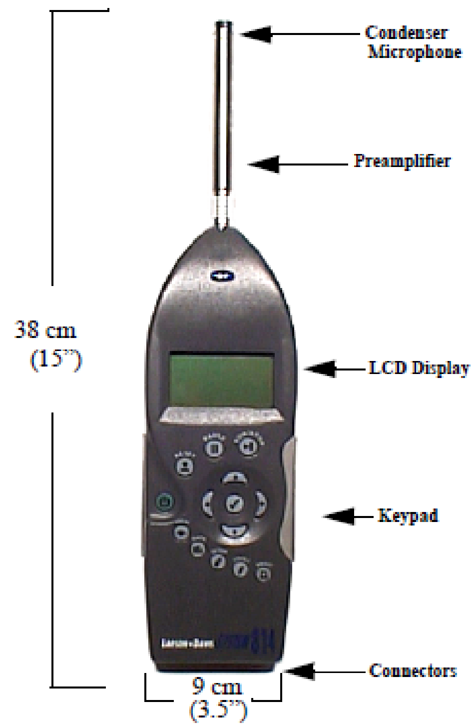


Figure A.C1 Larson Davis sound level meter

The use of additional equipment such as lockable “outdoor measurement case” is necessary if the sound level meter is going to be left unattended in the field (Figure A.C2). The body of the instrument is located in the outdoor measurement case. Through the holes located on the sides of the case, the microphone extension cable can be run from the case to the target location of the microphone.

Figure A.C2 Set of equipment necessary for continuous noise level measurement

Placement of sound level meter is critical to capture accurate sound samples. When appropriate, a sound level meter can be place on a tripod as shown in Figure A.C3.

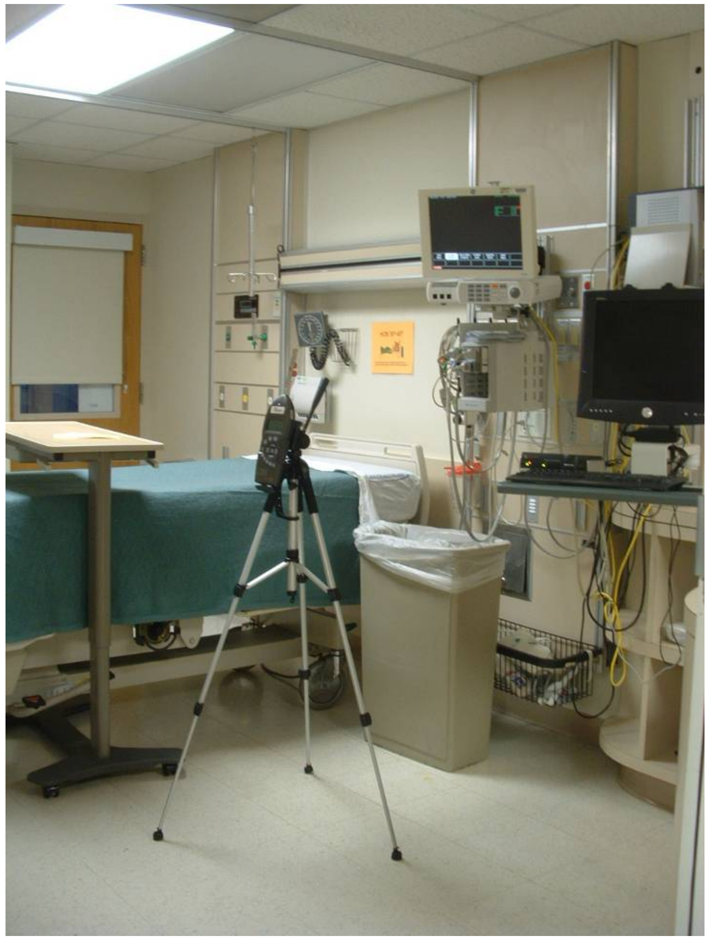


Figure A.C3 Placement of sound level meter in an unoccupied patient room

In the clustered occupied patient rooms, the use of tripod might not be practical. A practical solution can be hanging the microphone from the ceiling while leaving the instrument in the case (Figure A.C4 and Figure A.C5).

Figure A.C4 Placement of a single channel microphone in an occupied patient room

When applicable the microphone can also be placed on one of the medical equipment surrounding the patient such as medical boom (Figure A.C5).

Figure A.C5 Placement of a single channel microphone in a ward

Figure A.C6 Placement of a single channel microphone at a nurse station

APPENDIX D: NOISE LEVEL MEASUREMENT GUIDE

SLM Background Noise Measurement Guide

Equipment:

- PCB Piezotronics Microphone in Blue Case.
- Larson-Davis PRM 902 Preamp
- Larson-Davis System 824 Sound Level Meter (SLM)
- Adjustable Tripod
- Extension Cord
- Range Finder or Tape Measure

SLM Assembly:

NOTE: ALWAYS KEEP SOUND LEVEL METER OFF DURING ASSEMBLY AND DISASSEMBLY

1. Insert preamp into the SLM, making sure to align the red dot with the corresponding mark on the SLM. Preamp should lightly "click" into place.

Figure 1. Connection of SLM and Preamp

2. Gently screw the microphone onto the top of the preamp. Be extremely careful to hold the bottom (base) of the microphone and not the top, or the diaphragm could be damaged.

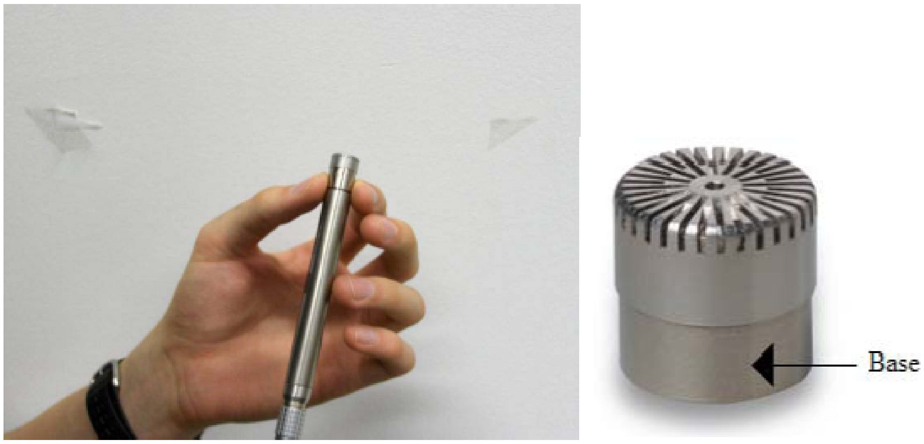


Figure 2. Connection of Microphone and Preamp

Figure 3. Assembled SLM

3. Plug in the SLM to a standard wall outlet using the provided adapter (See Figure 4). Turn on the SLM by pressing the green power button. It is preferable, and sometimes necessary, to plug in SLM, rather than to run on battery power.

Figure 4. Bottom View of SLM SLM Calibration:

1. Attach acoustic calibrator (set at 114 dB) to the sound level meter microphone by pressing it into the microphone head firmly. The calibrator should lightly snap onto the microphone head and remain on the microphone when the SLM is turned sideways

2. Press the calibrator's 'ON' button, which protrudes from the side. A calibration tone will be played for several seconds, although it may not be audible more than a few feet away.

On the SLM, press: *Tools: Calibration:* ► *: Check* ✓

4. Note the measured sound level. It should read close to 114 dB (*re* 20 μPa). If it does not, re-attach the calibrator and repeat Steps 2 & 3.

5. Remove the calibrator & return it to the SLM case.

Measurement Setup:

1. Attach the SLM to the tripod and set so that the <u>microphone</u> is at an approximate height of 1.55 m (This is average ear level). Place the microphone at least 1.5 m from reflecting surfaces (walls, equipment, protrusions) in all directions.

2. Use a range finder to measure the SLM's location. Record the location, including height and distance from walls/objects.

3. If off, power on the fully assembled SLM by pressing the Power ( ) Key. Wait for the hourglass in the top right corner to disappear before moving on.

4. Press the Setup ( ) Key.

5. Scroll down to "SLM&RTA" using the Directional (and) Keys.

6. With "SLM&RTA" highlighted, press the Select ( ) Key.

7. Once again, press the Setup ( ) Key. Highlight the first choice, Edit Settings: SLM&RTA.

8. Press the Right direction Key to edit the measurement settings

9. Scroll down to "Intervals." Press the Right direction Key.

10. Verify that Intervals are set to "On" and the Interval Time is set to the appropriate times. (Intervals are in HH:MM:SS Format, so to record every one minute, this clock should be set to 00:01:00).

11. Once verified, use the Left direction Key to return to the Setup Menu

12. Press the View ( ) Key.

13. Scroll down to "SLM" using the Directional (and) Keys.

14. With "SLM" highlighted, press the Select ( ) Key.

15. Clear any previous, unsaved data by pressing the Reset ( ) Key. Select "Current"

APPENDIX E: HOSPITAL NOISE SURVEY QUESTIONS

This study aims to compare the acoustical environments of two critical care settings therefore only nurses working at **Emory University 2D-Neurological ICU** and **5E-Medical Surgical Unit** can participate in this research.

- Please select which unit you work in.

☐ **2D-Neurological ICU**

☐ **5E-Medical Surgical ICU**

Your Profile

1-Gender:

☐ Male ☐ Female

2-Age:

☐ 20-24 ☐ 25-29 ☐ 30-34 ☐ 35-39 ☐ 40-44 ☐ 45-49 ☐ 50-54 ☐ 55-60 ☐ 60+

3-How many years have you worked as a critical care nurse during your entire career?

☐ <1 ☐ 1-3 ☐ 4-6 ☐ 7-9 ☐ 10 and 10+

4-How many years have you worked at your present place of employment (2D-NICU;5E-MedSurg)?

☐ <1 ☐ 1-3 ☐ 4-6 ☐ 7-9 ☐ 10 and 10+

5-When do you typically work? Please check all that apply.

☐ 7am-7pm ☐ 7pm-7am ☐ 11am-11pm ☐ 11pm-11am ☐ 7am-3pm ☐ 3pm-11pm ☐ 11pm-7am

☐ If other please specify: ______________________

6-Which job category describes you?

☐ PRN ☐ Full time RN

☐ Part time RN

7- When do you typically work?

☐ weekdays

☐ weekends

☐ both weekdays and weekends

8-How many hours in a week do you typically work?

☐ <12 ☐ 12 ☐ 24 ☐ 36 ☐ 48 ☐ 48+

Key sounds and key locations in your workplace

1- Please rate your agreement that the following are critical care nurse tasks for patient monitoring. Phrase "critical sounds" refers to alarms, patient bodily sounds (i.e. respiratory variations), help calls and patient safety threatening sounds (i.e. leaking air from air tube, patient/staff fall...etc).

	1 completely disagree	**2 somewhat disagree**	**3 neither agree nor disagree**	**4 somewhat agree**	**5 completely agree**
Ability to hear the critical sounds for patient safety is a crucial task for critical care nurses.	☐	☐	☐	☐	☐
Ability to differentiate the critical sounds for patient safety is a crucial task for critical care nurses.	☐	☐	☐	☐	☐
Ability to effectively guess the location of the critical sounds is a crucial task in critical care nursing.	☐	☐	☐	☐	☐
Overall auditory monitoring (listen, recognize and respond to the critical sounds) is a crucial task in critical care nursing.	☐	☐	☐	☐	☐
Visual patient monitoring is a crucial task in critical care nursing.	☐	☐	☐	☐	☐
Overall, I can usually guess the location of the critical sounds in my workplace.	☐	☐	☐	☐	☐
Overall, I can usually hear critical sounds in my workplace.	☐	☐	☐	☐	☐

2- According to your experiences, please indicate how critical are the following alarms for patient safety?

	1 not at all	**2 somewhat**	**3 very**
IV pump alarm	☐	☐	☐
Ventilator alarm	☐	☐	☐
Patient monitor alarm	☐	☐	☐
Feeding pump alarm	☐	☐	☐
Nurse call	☐	☐	☐
Ventilator hissing sound	☐	☐	☐

If there are others, please indicate them and provide associated ratings

____

3- Other than medical alarms, what type of sounds do you believe necessary to listen to for the safety of patients, staff and visitors?

4- Please tell us, during your shift how often do you monitor the critical sounds (from your patients` rooms) at the following locations?

	1 rare	2 moderately	3 very often
Corridor	☐	☐	☐
Patient room	☐	☐	☐
Alcove	☐	☐	☐
Centralized nurse station	☐	☐	☐
Medication room	☐	☐	☐
Supply room	☐	☐	☐

If there are others please indicate them and provide associated ratings:________________________________

Subjective ratings of the sound environment in your workplace

1- Please select one of the following if you are working in 2D-NICU:

☐ my responses for the following 3 questions will be specific to 2D-East.

☐ my responses for the following 3 questions will be specific to 2D-West.

☐ my responses will reflect my overall experience in the 2D-NICU.

2- Please indicate how you typically experience the sound environment at **different locations** in your workplace.

	at the centralized nurse station					in the alcoves					in the **empty** patient rooms					in the **occupied** patient rooms					in the corridors				
	1 not at all	2	3	4	5 very	1 not at all	2	3	4	5 very	1 not at all	2	3	4	5 very	1 not at all	2	3	4	5 very	1 not at all	2	3	4	5 very
How **annoying** is the noise at different locations in your unit?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
How **loud** is the noise at different locations in your unit?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

3- Please indicate how you typically experience the noise levels at your workplace at different times during the **weekend.**

	During the shift changes						During the day times						During the night times						Overall					
	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know
How **annoying** is the noise in your unit during the weekend?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
How **loud** is the noise in your unit during the weekend?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

4- Please indicate how you typically experience the noise levels at your workplace at different times during the **weekdays.**

	During the shift changes						During the day times						During the night times						Overall					
	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know	1 not at all	2	3	4	5 very	I don't know
How **annoying** is the noise in your unit during the weekdays ?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
How **loud** is the noise in your unit during the weekdays ?	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Overall loudness levels and its impacts

1- Please indicate how you typically experience the sound environment at your workplace

	1 completely disagree	2 somewhat disagree	3 neither agree nor disagree	4 somewhat agree	5 completely agree
My workplace is very loud.	○	○	○	○	○
I find *alarms* particularly very loud in my workplace.	○	○	○	○	○
I sometimes tune out the alarms.	○	○	○	○	○
I find the *noise* very annoying in my workplace.	○	○	○	○	○
I find the *alarms* particularly very annoying in my workplace.	○	○	○	○	○
The *noise* in my workplace negatively affects my work performance.	○	○	○	○	○
The *alarms* in particular negatively affect my work performance.	○	○	○	○	○
The noise at work is a small problem compared to other working environment problems.	○	○	○	○	○
The *noise* in my workplace negatively affects my health.	○	○	○	○	○
The *alarms* in particular affect my health.	○	○	○	○	○
The *noise* in my workplace increases my anxiety level.	○	○	○	○	○
The *alarms* in particular increase my anxiety level.	○	○	○	○	○

2- Please indicate if you have any specific suggestions based on your experiences and observations to improve the acoustic environment in your workplace.

General hearing

1-Have you had a hearing test in the last five years?

☐ No

☐ Yes. Please indicate what the results were: ________________________________

2-Do you have any known hearing impairments?

☐ No ☐ I don`t know.

☐ Yes . Please explain ______________________

3-Do you have difficulties understanding speech in an environment where there are several others talking at the same time?

☐ No ☐ Yes

4-How would you evaluate your hearing?

☐ Very bad ☐ Bad ☐ Normal ☐ Good ☐ Very good

Noise Sensitivity

1- Regarding noise in general, do you feel:

☐ Not at all sensitive to noise

☐ Not particularly sensitive to noise

☐ Fairly sensitive to noise

☐ Very sensitive to noise

2- What kind of sound environment do you think is acceptable for you at your workplace?

☐ 1 ☐ 2 ☐ 3 ☐ 4 ☐ 5:

1: Complete quiet is the only thing that I can accept
5: I can accept high sound level

APPENDIX F: OCCURRENCE RATE

This appendix aims to provide more information about occurrence rate analysis. Occurrence rate represents the % of the time during which background noise levels exceeded specified peak and maximum sound pressure levels. This study considered maximum sound pressure values of 70dB, 80dB and 90dB and peak sound pressure levels of 80dBC, 90dBC and 100dBC as the threshold values. It was mainly because the occurrence rates of maximum sound pressure levels less than 70dB and higher than 90dB, and the occurrence rates of peak sound pressure levels less than 80dBC and more and 100dBC did not differ much in the two hospital settings.

Figure A.F1represents the sound pressure levels associated with different sound events to enable cross comparisons. However it needs to be noted that not only sound level but also other qualities of sound events such as frequency content and duration can also significantly affect annoyance and loudness perceptions of the human auditory system.

Figure A.F1. Sound pressure levels associated with different sound events

There are not many detailed guidelines providing allowable exposure times to maximum and peak sound levels. According to OSHA, exposure to an impulsive noise event should not exceed 140dB peak sound pressure level (OSHA, Occupational Safety and Health Standards). According to WHO, Lmax sound pressure levels should not exceed 40dB in the hospital settings particularly in the patient rooms (Berglund et al., 1999).

Calculation of occurrence rate:

To calculate occurrence rates, peak and maximum sound pressure levels are documented every minute (a.k.a. 1-minute interval) during the study period. Then peak and maximum sound pressure levels are compared with the specified levels as shown in Figure A.F2.

SSA Intervals		
Translated:	3-Feb-09	18:45:38
Weighting:	Flat	
Peak Weighting	C	
Detector:	Fast	
RTA Detector:	Fast	

Rec #	Date	Time	Duration	LMax	>70dB	>80dB	>90dB	Peak	>80dBC	>90dBC	>100dBC
2296	31-Jan-09	7:00:17	01:00.0	74.9	1	0	0	90.7	1	1	0
2297	31-Jan-09	7:01:17	01:00.0	80.7	1	1	0	101.8	1	1	1
2298	31-Jan-09	7:02:17	01:00.0	80.3	1	1	0	99.5	1	1	0
2299	31-Jan-09	7:03:17	01:00.0	74.4	1	0	0	84.0	1	0	0
2300	31-Jan-09	7:04:17	01:00.0	74.2	1	0	0	83.3	1	0	0
2301	31-Jan-09	7:05:17	01:00.0	73.9	1	0	0	85.9	1	0	0
2302	31-Jan-09	7:06:17	01:00.0	79.1	1	0	0	92.9	1	1	0
2303	31-Jan-09	7:07:17	01:00.0	75.0	1	0	0	87.0	1	0	0
2304	31-Jan-09	7:08:17	01:00.0	78.1	1	0	0	98.9	1	1	0
2305	31-Jan-09	7:09:17	01:00.0	76.5	1	0	0	96.7	1	1	0
2306	31-Jan-09	7:10:17	01:00.0	78.0	1	0	0	87.8	1	0	0
2307	31-Jan-09	7:11:17	01:00.0	74.9	1	0	0	87.5	1	0	0
2308	31-Jan-09	7:12:17	01:00.0	78.2	1	0	0	92.7	1	1	0
2309	31-Jan-09	7:13:17	01:00.0	79.6	1	0	0	89.9	1	0	0
2310	31-Jan-09	7:14:17	01:00.0	82.1	1	1	0	95.1	1	1	0
2311	31-Jan-09	7:15:17	01:00.0	79.3	1	0	0	92.5	1	1	0
2312	31-Jan-09	7:16:17	01:00.0	80.6	1	1	0	94.6	1	1	0
2313	31-Jan-09	7:17:17	01:00.0	78.8	1	0	0	96.6	1	1	0
2314	31-Jan-09	7:18:17	01:00.0	74.4	1	0	0	90.1	1	1	0
2315	31-Jan-09	7:19:17	01:00.0	80.8	1	1	0	100.1	1	1	1
2316	31-Jan-09	7:20:17	01:00.0	81.6	1	1	0	87.5	1	0	0
2317	31-Jan-09	7:21:17	01:00.0	73.4	1	0	0	86.3	1	0	0
2318	31-Jan-09	7:22:17	01:00.0	77.4	1	0	0	83.5	1	0	0
2319	31-Jan-09	7:23:17	01:00.0	74.8	1	0	0	89.7	1	0	0
2320	31-Jan-09	7:24:17	01:00.0	77.7	1	0	0	87.4	1	0	0
2321	31-Jan-09	7:25:17	01:00.0	75.7	1	0	0	88.9	1	0	0

Figure A. F2. Example acoustic data set used for the calculation of occurrence rate of maximum and peak sound pressure levels.

Different from occurrence rate analysis, traditional metrics used to assess impulsive characteristics of sound environments only consider the highest LMax and LPeak values that occurred during the study period. In other words, they represent the characteristics of a single highly impulsive noise event. Overall, compared to traditional metrics, occurrence rate analysis of LMax and LPeak sound pressure levels provide a better picture of the impulsive characteristics of sound events. Therefore, in addition to traditional metrics, the use occurrence rate analysis can be highly important.

APPENDIX G: IMPULSE RESPONSE FIELD MEASUREMENTS

This appendix introduces the details of gathering impulse response of a room by conducting field measurements. The use of different equipment is necessary for this type of field measurement (Figure A.G1). The microphone is located at the receiver position. It captures the room response to a sound burst produced by the sound source located at another location. In particular, the ISO 3382-1 standard suggests the use of an omni-directional sound source and an omni-directional microphone to measure the reverberation time (ISO 3382-1). Some other components of the system that were used in this study included an Outline amplifier, ProSonus EASERA Gateway data acquisition system (DAQ) and lap-top equipped with EASERA software v1.1 (Figure A.G2). The DAQ system enables the data transfer between different system components including amplifier, lap-top, and microphone.

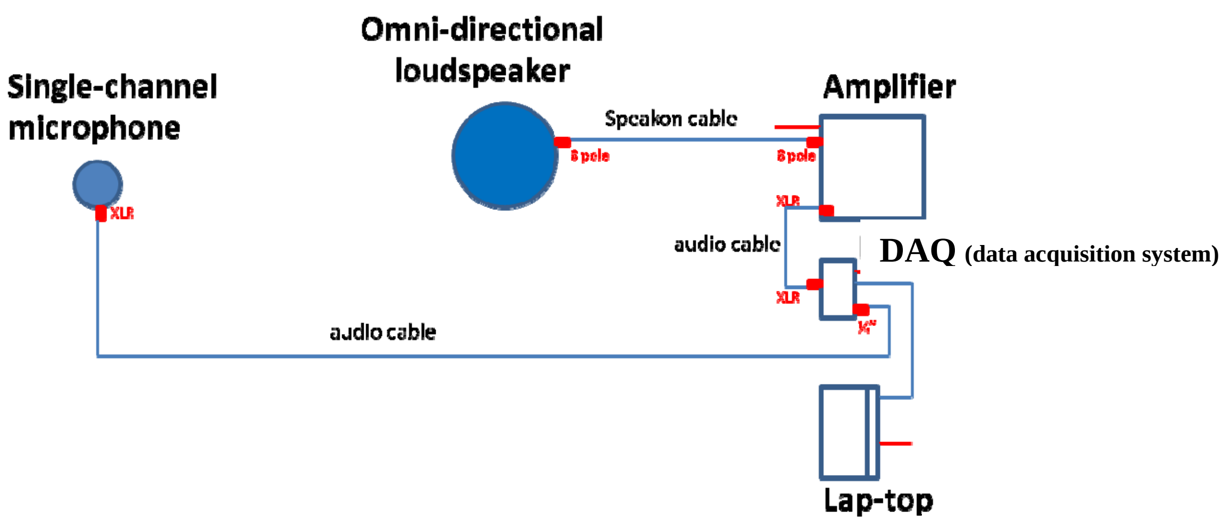


Figure A.G1 Diagram showing the set up of impulse response equipment

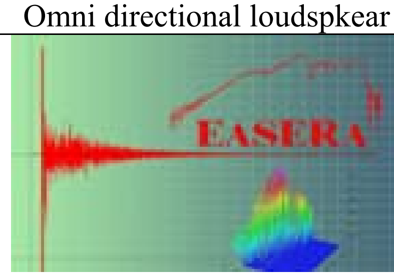
 Speakon cable	 Connector
 Audio cable	 Amplifier
 ProSonus EASERA Gateway Box	 Omni directional loudspkear
 Single-channel microphone	 EASERA software

Figure A.G2 Individual components of the impulse response measurement

Maximum Length Sequence (MLS) Method vs. Others

Different sound signals can be used during for impulse response measurements. A commonly used signal is the “sine sweep” which consists of a swept sine wave with a frequency sweeping over the desired frequency range (Figure A.G3). This is not a random signal and the extracted impulse response is free from noise contributed from the excitation signal. It is considered as a weighted sum of delayed impulses with defined weighting factors (Acoustics Engineering, 2007). By deconvolving the sweep signal with source signal, room impulse response is obtained.

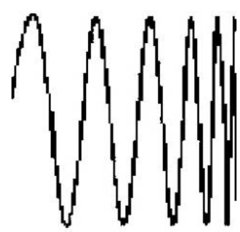


Figure A.G3 Shape of the swept sine signal

In this study, a maximum length sequence (MLS) signal was used. It is a periodic, pseudorandom white noise signal. Its frequency spectrum over one period is flat (Figure A.G4). It is considered as the weighted sum of delayed impulses with weighting factors +1 and -1 (Acoustics Engineering, 2007). By calculating the cross-correlation between the MLS and the signal at the receiver location, the room impulse response is obtained. Due to cross-correlation, non-correlated noise including the competing background noise is rejected. Therefore, the extracted impulse response is therefore not “polluted” by any noise due to the excitation signal. It is one of the reasons why this method enables more reliable impulse response results in noisy environments such as HVAC background noise.

For reliable results, ISO 140 Standard recommends 6dB as the minimum acceptable value for Signal-to-Noise ratio (ISO 140 Standard).

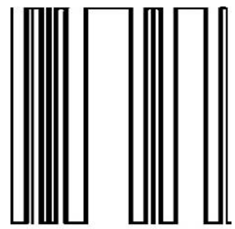


Figure A.G4 Shape of the MLS signal

EASERA

EASERA is a software package used for the estimation of room-acoustics parameters such as reverberation time from room impulse response. EASERA`s post processing engine calculates all acoustic functions and measures according to ISO Standard 3382 based on octave or 1/3 octave filters (EASERA Tutorial). The impulse response of a room can be captured via EASERA by using a variety of excitation signals such as sine sweep, white and pink noise and MLS signal as shown in Figure A.G5.

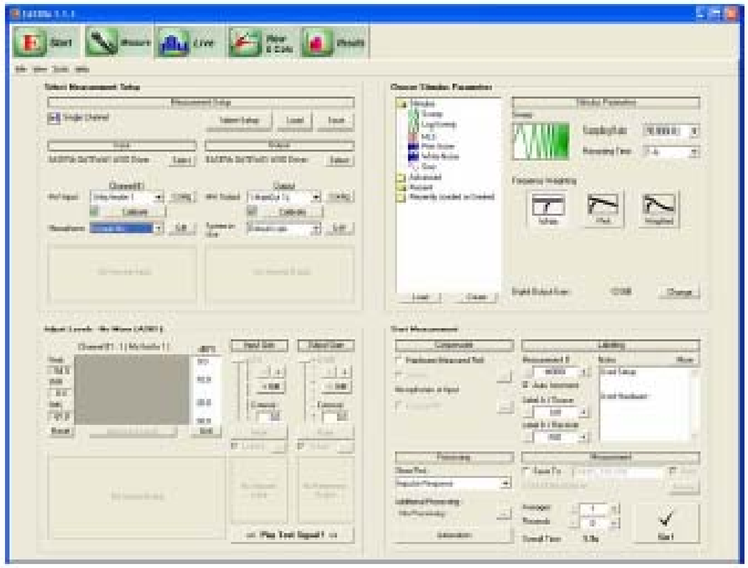


Figure A.G5 EASERA interface

Critical Distance

The energy of the sound source decreases by distance. The distance where both energy densities of the direct and reflected sound are equal is called "critical distance" (Kutruff, 2000). The total energy of the sound is the sum of direct sound and reflected sound. Inside the reverberation radius (a.k.a. critical distance) direct sound is dominant, however beyond the reverberation radius the effect of direct sound is negligible as shown in Figure A.G6.

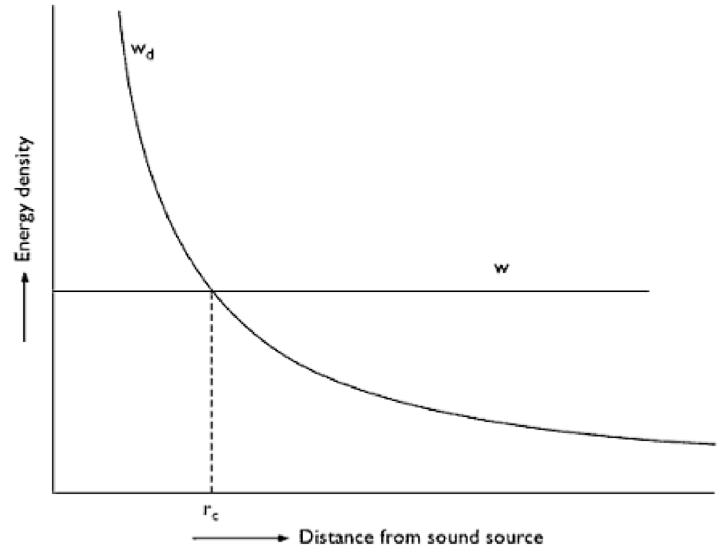


Figure A.G6 Critical distance graph (from Kutruff, 2000)

Conducting impulse response measurements outside the reverberation radius is important as most times the main interest of acousticians is the assessment of reflections caused by the enclosure boundaries. The following formula is used for the calculation of the critical distance. The critical distance (r_c) is in meter. "A" is the total absorption area and equal to Sxa. "S" is the total surface area and "a" is the average absorption coefficient of surfaces in the room.

$$r_c = \sqrt{\frac{A}{16\pi}}$$

APPENDIX H: IMPULSE RESPONSE MEASUREMENT GUIDE

MLS Measurement Technique for Corridors

Equipment:

- Laptop equipped with EASERA software
- ProSonus EASERA Gateway
- Instrumental Microphone
- Microphone Stand w/ Mic clip
- Omni-directional sound source (speaker)
- 6-pin to 4-pin Firewire cable
- XLR – XLR Cable
- ¼" to ¼" Cable

Measurement Setup:

- Place omni-directional sound source at least 1.5 m away from reflecting surfaces.
- Attach the instrumental microphone to the microphone stand using the microphone clip.
- Place the microphone at least 1.5 m away from reflecting surfaces, including the floor. The microphone should be at least 3 meters away from the sound source.
- Attach the microphone to the ProSonus EASERA gateway using the XLR-XLR cable. Attach the sound source to the gateway's output using the ¼" to ¼" cable
- Connect the "Impulse Laptop" to the EASERA Gateway using the 6-pin (Gateway) to 4-pin (Laptop) Firewire Cable. When all equipment is turned on, the Gateway should display a blue light in the Firewire indicator. If this light is red, there is a loose connection.

Procedure

- Open EASERA program. Select the Measurement tab from the button list on the left side of the program window. Confirm that "EASERA GATEWAY ASIO Driver" is listed as the input and output on the first window.
- Select the "MLS" stimulus signal. The length of time and sampling rate of the signal can be adjusted based on the needs of the space. Use white-noise weighting.
    - Note: ISO standards suggest the length of signal be no shorter than the T_{60} time of the space in question. For this reason, 11 seconds was used during testing of this method.
- On the next window, play a test signal to adjust the volume of the loudspeaker to an appropriate Signal-to-Noise ratio (SNR). During testing, an SNR value of 2.0 was used. This may not be possible in an occupied setting.
- On the "Start Measurement" window, confirm that the Impulse Response is shown first, under the processing section, and a file name to save the resulting data. The averages and presends can be adjusted here, as well.
- After clicking the "Go!" box, EASERA will play the MLS signal through the sound source for the given time. EASERA will record the initial response of the microphone to the excitation. The impulse response will then be displayed.

APPENDIX I: COMPUTER MODELING

Different theories have been developed to describe sound behavior in enclosed spaces such as wave-based acoustics and geometric acoustics. Wave based acoustics considers sound as pressure waves. Some of the computer simulation methods developed based on wave-based acoustics principles include Finite Element Method (FEM) or the Boundary Element Method (BEM). However, these methods are often not practical for architectural acoustics because the number of modes in a room increases rapidly as frequency increases. Therefore, the use of these methods is typically limited to predict the acoustics of small rooms and low frequencies (Smith, 2004). Geometric acoustics consider sound as rays, similar to light rays used in the field of optics that propagate in straight lines. This consideration assumes that the dimensions of a rooms are large compared to the wavelength of the sound. In small rooms, this assumption does not always hold for the low frequency sounds because wavelengths of low frequency sound is larger compared to wavelengths of high frequency sounds. Related with this, the use of geometric acoustics is typically limited to frequencies of 250Hz and above in small rooms. Computerized acoustic modeling programs have been developed based on geometric acoustics theory that are capable of simulating different behaviors of sound in the enclosed spaces such as specular reflection, diffuse reflection and absorption. These programs most times do not take into account diffraction. However, recent advances in computer simulation programs enabled the development of algorithms that emulate diffraction from edges. This topic is discussed in more details below.

Some of the computer simulation methods developed based on geometric acoustics principles include ray tracing, image source method, and hybrid method. In the following section, the qualities of each method are introduced based on the information gathered from following sources: Smith 2004, Long 2006, CATT manual, and Odeon Manual. Some information about the Radiosity method is also included below. Kang (2002a) used this method for the theoretical studies introduced in Chapter 4.

Ray Tracing

In acoustic modeling applications that use a ray tracing method, a source emits a finite number of rays representing the sound waves in either an omni-directional pattern (i.e., spread of sound rays in every direction) or in a specific pattern based on the directivity of the sound source (Figure A.I1). The ray tracing method predicts numerical acoustic measures by tracing acoustic rays based on the rules of the geometric acoustics (e.g., generating specular and/or diffuse reflections) and using statistical methods to calculate energy loss via absorption. The sound rays are traced until they reach a virtual listener represented with a sphere. Detection of the sound ray is significantly influenced by the size of the detector. For example, a large spherical detector will record a large number of hits from the rays compared to a receiver represented with a smaller sphere. By recoding the energy, direction and arrival time of sound rays, the program generates an echogram displaying the strength of the reflections at the receiver location over time. One of the main advantages of the ray tracing method is the shorter computation time because the sound source emits sound rays randomly. The computational time is proportional to the number of rays and the order of the reflections used. Another advantage of this method is that multiple receivers at different locations can be investigated because sound is emitted in every direction.

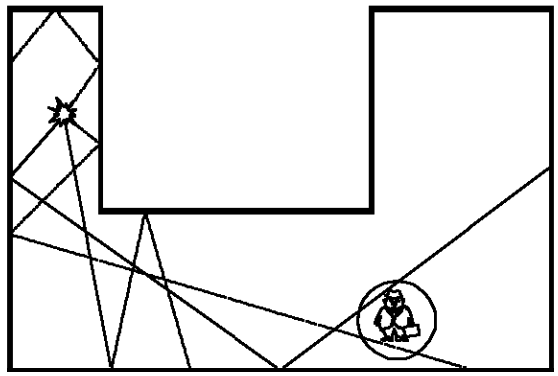


Figure A.I1 Distribution of sound rays in an enclosed space (only rays crossing the circle contribute to the impulse response calculations)

Image Source Modeling (ISM)

ISM method determines specular reflections between source and receiver. It generates the images of the sound source known as *virtual sources* or *image of the source* (Figure A.I2).

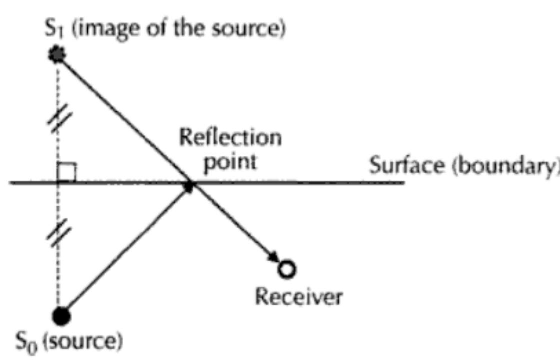


Figure A.I2 Image of a sound source (from Cheenne, 2002)

These virtual sources replace the boundaries of the room as shown in Figure A.I3 (Cheenne, 2002). ISM first calculates the first order image sources of the main sources in all reflecting planes. From each of these first order image sources, second order sources are created by calculating new images sources in all reflecting planes. This procedure is repeated until the order of reflection and arrival time defined by the user. Once all image sources are found, the program calculates arrival times by calculating the length of each image source to the receiver. The amplitude of each reflection is calculated from the output power and directivity of the source and is adjusted by absorption and diffusion properties of the planes as well as air absorption.

This method concerns only with the sound reflections reaching the receiver and ignores reflections that do not reach the receiver. It collects the amplitude, arrival time and the direction of all reflections. The echogram is provided by summing the contribution of each image source with corresponding delays and attenuation (Tsakostas, 2004). It needs to be noted that, each virtual source contributes only a pure impulse of known strength and delay in the time domain.

In particular, this method has been mainly preferred because of its effectiveness in handling the early arriving energy or low-order reflections (i.e., direct sound, first and second order reflections) (Monks, Oh, & Dorsey, 1996).

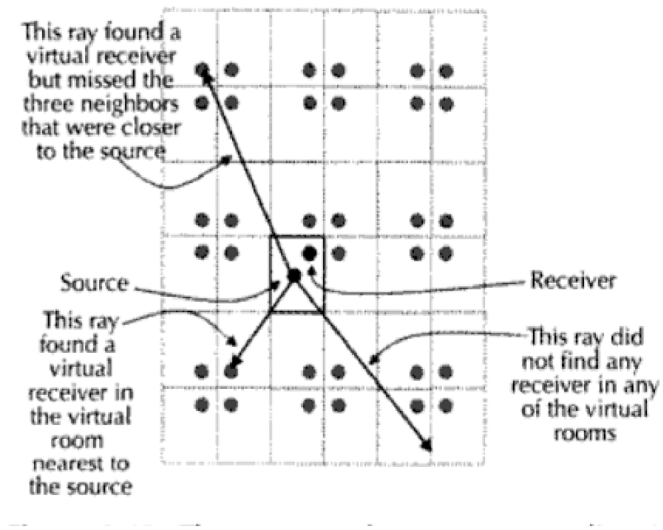


Figure A.I3 Distribution of sound source images (from Cheenne, 2002)

Hybrid Method

Hybrid algorithms have been developed to optimize the best features of two different acoustic prediction models: image source model (ISM) and ray tracing (RT). The hybrid method is the most up-to-date prediction method. Hybrid algorithms uses ray tracing method to determine the valid image sources. Each ray detected by a receiver is associated with an image source. These image sources are found by tracing it back from the receiver location. To keep track of the valid image source, “image tree” is created. Hybrid methods handle early and late reflections differently by incorporating the best features of ISM and ray tracing methods. Often the image source method is used to predict the early part of the impulse response and mostly ray tracing methods is used to predict the late part of the impulse response.

Acoustic modeling programs such as CATT and ODEON use a hybrid algorithm. These hybrid methods may vary based on the type of receiver used such as cone, beam and pyramid tracing vs. ray tracing. In this study CATT Acoustics V8 is used. In CATT V8, Early Part Detailed ISM prediction method uses the image source method to calculate the early part of the echogram which is an approximation to the squared impulse response of a room (Smith, 2004; CATT manual). The Full Detailed Calculation prediction method uses Randomized Tail-Corrected Cone tracing (RTC) or Late-Part Ray Tracing. The use of latter option is suggested for coupled rooms, and rooms with complex floor-plate shapes.

Radiosity Method

The radiosity method has been predominantly used to calculate light energy. It is considered to be applicable in acoustics when used for high frequency band (Kang, 2002a). The radiosity method divides boundaries into a number of patches and distributes the sound energy of an impulse source to patches (Figure A.I4). The patches are then determined as sound sources which redistribute the sound energy to other patches. In summary, this method calculates the energy response at the receiver locations by calculating the energy exchange between patches.

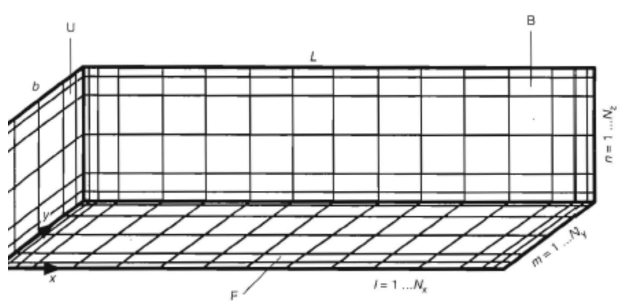


Figure A.I4 Patches used in the Radiosity method (from Kang, 2002a)

Acoustic Modeling User Settings

Behaviors of sound commonly predicted by the computer simulation programs include diffuse reflection, geometric reflection and absorption. With recent developments, diffraction can also be predicted by some programs. For the accuracy of the predicted acoustic outcomes and simulation of sound behaviors in enclosed spaces, user selected parameters are highly necessary.

Diffuse vs. geometric (specular) reflection

In accordance with "law of reflection", a light/sound ray is reflected from the boundary surfaces with a predictable manner. Reflection off smooth surfaces leads to a reflection known as "specular reflection". As a rule of thumb, the angle of the incidence is equal to the angle of the reflection for specular reflections (Figure A.I5). Specularly reflected sound rays remain concentrated in a bundle upon leaving the surface. Reflection off rough surfaces leads to a type of reflection known as "diffuse reflection". Diffusely reflected sound rays diffuse in many different directions. Diffusive qualities of boundary surfaces are significant for acoustic outcomes such as reverberation time (RPG Diffuser Systems). For example, when the surfaces of a room are diffusely reflective, there is more chance that the sound rays will hit various surfaces including walls and ceiling (where most time absorbers are located). Diffusely reflective surfaces also provide more uniform distribution of acoustic qualities in a room.

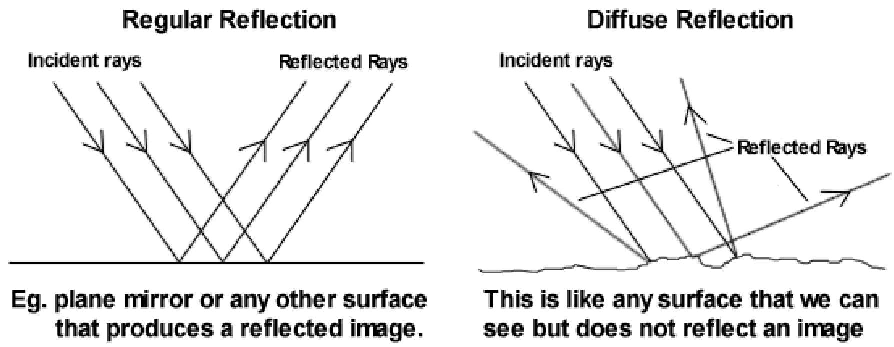


Figure A.I5 Sound reflections off diffusely and geometrically reflective surfaces (from Cheenne, 2002)

Scattering coefficient

Scattering coefficient is a parameter used in acoustic simulation programs to quantify diffusely reflective qualities of the boundary surfaces. It is a measure of the total amount of sound scattered randomly from the boundary surfaces in relation to total reflected sound energy as shown in the equation below.

$$\delta = \frac{\text{non - specularly reflected sound energy}}{\text{total reflected sound energy}}$$

The energy that is not scattered is absorbed or specularly reflected by the boundary surfaces. In more detail, if the incident energy is normalized to1, the total reflected sound energy (that is not absorbed by the surface) will be (1-α) where α is the absorption coefficient. This energy is used for specular and diffuse reflections. The component of the sound energy that is specularly reflected is considered as (1- α)(1-δ) and the component that is non-specularly reflected (scattered) is considered as (1- α) δ (Figure A.I6).

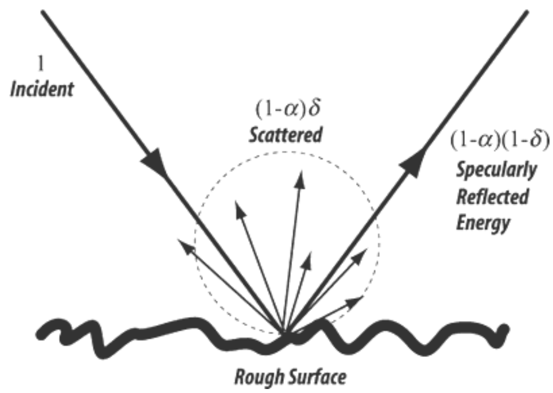


Figure A.I6 Diffusely and specularly reflected sound rays off rough surfaces (from Cheenne, 2002)

Rough surfaces are assigned higher values of scattering coefficients to indicate more scattering of the sound compared to smooth surfaces. The CATT-Acoustics manual provides some guidelines for approximating the scattering coefficients of the surfaces. A minimum of 20% scattering is recommended for an average size, flat, smooth surfaces and 10% for larger flat and smooth surfaces. Some of the other surfaces that CATT specifies scattering coefficients include audience areas (suggested scattering coefficients range between 30% and 70%) and rough surfaces with 0.3m surface roughness (suggested scattering coefficient is as high as 80%). In conditions of doubt, assigning higher values of scattering coefficient rather than assigning lower values is suggested.

Absorption coefficient

All surface materials absorb sound to some degree and the rest is reflected or transmitted (Figure A.I7). Materials that are specifically employed for the purpose of absorbing sound are called “sound absorbing materials”. A standard method of rating the effectiveness of a sound absorbing material is by its absorption coefficient. The absorption coefficient varies with the frequency of sound. In other words, a surface material does not absorb the sound similarly across frequencies. To enable comprehensive analysis of absorption of different frequencies sound, absorptive qualities of materials are reported across frequencies. Absorption coefficients of a material can vary greatly across frequencies. However, it is likely that a reflective material has low values of absorption coefficients compared to absorptive material. In architectural spaces, values of absorption coefficient in six octaves ranging from 125Hz to 8kHz is typically considered, though the range can vary in some instances.

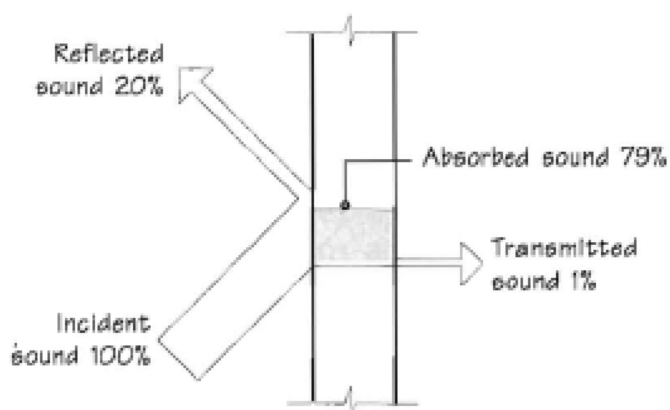


Figure A.I7 Reflected, absorbed and transmitted sound (Mehta et al., 1999)

Automatic edge diffusion

Sound is capable of traveling around the corners. In wave-based acoustics, sound is described as pressure waves. Bending of pressure waves around obstacles such as corner of buildings and walls of interior spaces is known as “diffraction”. Reflection alone does not account for all the indirect/reflected sounds at the receiver location. Diffraction also contributes to qualities of the sound at the receiver location, particularly at the receiver locations where the direct sound is not present (a.k.a. non-visual sound field). For example, outdoors a person around the corner of a building can hear us even if there is no reflection and direct sound. When sound diffracted in air at standard conditions, its speed, frequency and wavelength generally remain unchanged, since the wave remains in the same medium.

Recent developments in computer simulation research also suggest algorithms that can predict diffraction caused by the object edges such as doors and windows or boundary surfaces. For example, CATT Acoustics V8 offers an "automatic edge diffusion" function which takes into account the impact of diffraction on sound quality at the receiver locations. To emulate the diffusing effects of diffraction, a plane is assigned automatic frequency dependent edge diffusion. Briefly, reflections falling within a quarter of a wavelength from an edge are not specularly reflected but diffusely reflected as shown in Figure A.I8.

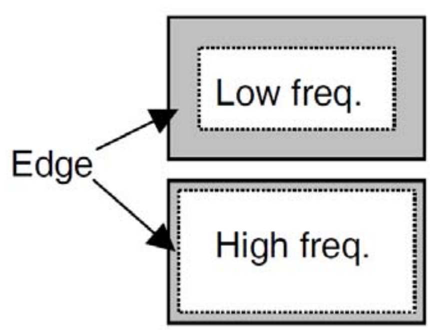


Figure A.I8 Reflective surfaces considered by frequency dependent "automatic diffusion function" of CATT (from CATT manual)

Number of rays

A user defined “number of rays” option is necessary to describe the amount of rays to be randomly emitted by the sound source. It is one of the significant factors that affect accuracy of predicted results. However, there are not commonly agreed solutions for calculating number of rays. CATT Acoustics V8 has an option where the program calculates the minimum number of rays needed for each particular acoustic model called “auto number” function.

Truncation time

Truncation time represents the length of time that the sound rays will be traced. There is not an agreed solution for calculating truncation time but it is suggested that truncation time should be set to at least 2/3 of the reverberation time. Similar to the “number of rays” option, CATT Acoustics V8 has an option where the program calculates the minimum truncation time needed (when selected).

Geometry modeling

Geometry files (also known as “GEO” files) include necessary information to describe the hall geometry in a text format. It also includes information about x, y, z coordinates of the planes corners, surface absorption and diffusion properties. The hall geometry can have any shape and can be composed of various planes (a max of 99,999 according to CATT). Entry of the geometry data can be defined either by using a text editor (Figure A.I9) or exporting the drawing from the AutoCAD interface (Figure A.I10). Once a set of Auto-LISP procedures are introduced to AutoCAD, the entire acoustic model (including all surface planes, source, receiver positions, plane names and absorption names) can be generated in the Auto-CAD environment. The geometry information is stored in a separate layer that can be exported as a GEO file compatible with CATT. This method has been applied widely as well as the text editor method. Martin and Arana (2006) indicated that they did not find any problem with this procedure.

```
;MASTFULL.GEO
;PROJECT:CATT-Acoustic tutorial for v8.0

;general materials defined here or from library

ABS wood   = <12 10 8 7 5 4>  {213 220 160}
ABS carpet = < 10 8 6 4 3 2 > {98 209 44}

ABS audience = <35 50 55 70 85 80> L <30 40 50 60 70 80> {128 128 0}
ABS floorabs = carpet

GLOBAL ah  = 1.0 ; audience height
GLOBAL rh  = 0.3 ; receiver height above audience plane
GLOBAL aww = 1.0 ; audience sidewalk widths
GLOBAL fsd = 1   ; front-stage depth
GLOBAL fsw = 6   ; front-stage width
GLOBAL sw  = fsw + 2 ; stage width
GLOBAL pw  = 2   ; prosc. width
GLOBAL w   = 16  ; max hall width
GLOBAL ew  = 1.4 ; entrance width
GLOBAL fld = 3   ; flank depth
GLOBAL flt = 1   ; floor tilt
GLOBAL wl1 = 6   ; first side wall length
```

Figure A.I9 CATT text editor interface

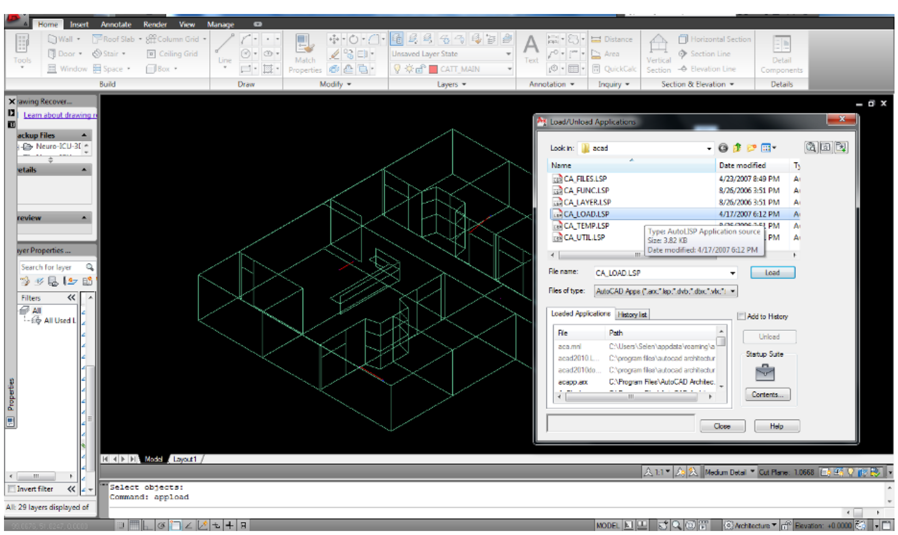


Figure A.I10 Auto-LISP commands used in Auto-CAD

It also needs to be noted that high levels of detail in the models do not necessarily improve the accuracy of the results. In fact, Bork (2000) argues that very detailed geometries could reduce the accuracy of the predicted results. Parallel with Bork`s (2002) argument, Naylor and Rindel (1992) suggest that an acoustic model should replicate the general forms of the room while avoiding unnecessary small surfaces and details. However, according to Bradley and Wang (2002) the level of model detail on predicted results does not affect the accuracy of predictions. In this study, related with these findings, instead of detailed models, simplified models were used.

Validity of Acoustic Modeling Programs

Acoustic modeling programs have been widely used by acoustic consultants and researchers, particularly for the acoustic analysis of rooms such as concert halls. The validity of these acoustic modeling programs, in particular the ones using the hybrid prediction method, in estimating the acoustic qualities of architectural spaces especially concert halls has been widely studied.

Martin and Arana (2006) compared the results of the impulse response measurements conducted in the new Symphony Hall in Spain with the predicted results by two acoustic modeling programs (P1 and P2) that use hybrid prediction method (Figure A.I11). In general the results provided by the two programs were similar but some differences occurred between predicted reverberation time and Ts levels.

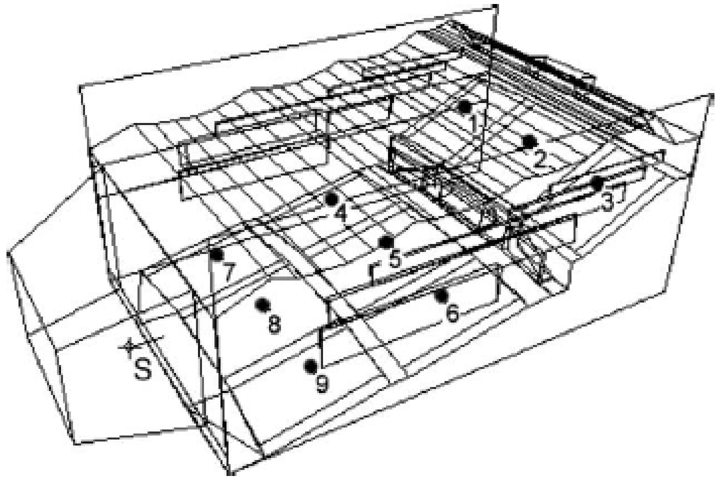


Figure A.I11 Three dimensional geometry of the Symphony Hall in Spain showing source and receiver locations (from Martin, & Arana, 2006)

In general across different frequencies, measured reverberation time results were higher compared to predicted results (Figure A.I12). Differences between predicted and measured results were generally perceptible for reverberation time and other measures such as Ts, C80, D50 and EDT based on the jnd thresholds suggested by ISO 3382. Compared to P2, the reverberation time results provided by P1 were generally higher and more similar to the measured results. Among the two programs, results provided by P1 followed a similar trend to the trend of the measured results. The key reason for such differences is potentially related with different algorithms used in the programs such as differently handled statistical corrections for late reflections and diffuse reflections. It was not explicitly mentioned in the study but based on the description of the program features, P1 was potentially CATT-Acoustics and the P2 was potentially ODEON. As mentioned earlier CATT and ODEON are two of the major acoustic modeling programs that use hybrid prediction method.

Overall, the study concluded that commercial acoustic modeling programs largely coincide with field measured results despite perceptible differences. This conclusion is only valid when we consider the similar trends followed by predicted and measured results. A similar trend line analysis is also used in this study to compare the predicted and measured results visually.

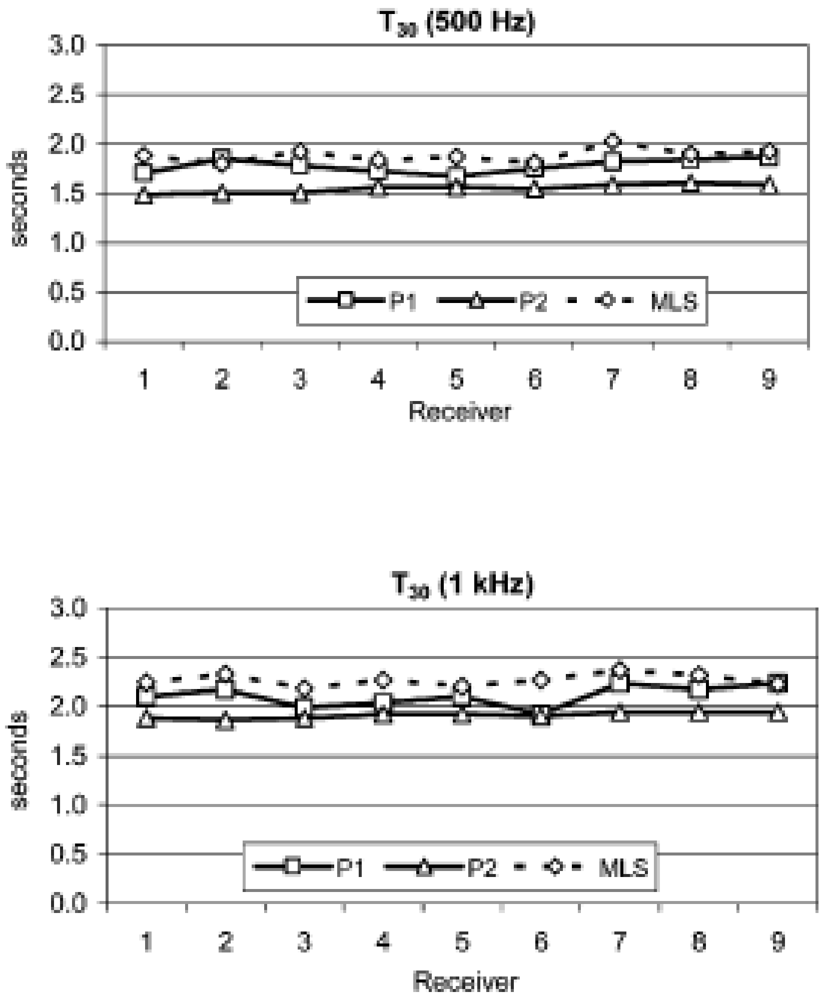


Figure 5.A.I12 Predicted vs. measured RT30 results at 500Hz and 1kHz (from Marin and Arana 2006)

Various Round Robin studies were also conducted to assess the effectiveness of different programs for room acoustics computer simulations. Vorlender (1995) compared the predicted results and measured results for a speech auditorium. In total, predicted results provided by 14 different acoustic modeling programs were considered. Each line in Figure A.I13 represents the predicted results by different modeling programs and the thick line represents the field measured results. The simulations were carried out by different participants independently and most of them were software developers. The results provided by only three programs using hybrid prediction methods were considered as reliable. The differences between measured and predicted results provided by these three programs were still perceptible based on ISO 3382 standards. Another important finding of the study was the significant impact of absorption coefficients on accuracy of the results.

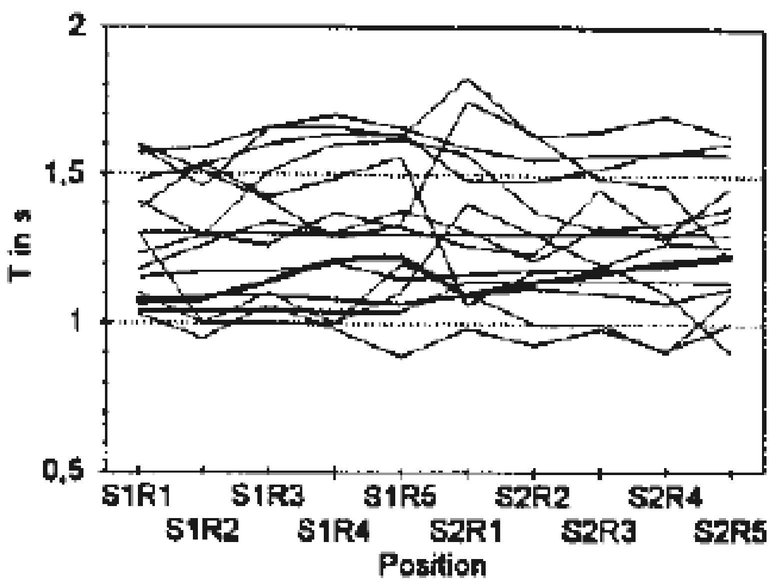


Figure A.I13 Reverberation time levels predicted for the same hall by different participants (from Vorlender, 1995)

Acoustic modeling of long enclosures

Various studies analyzed the effectiveness of acoustic simulation programs in predicting the acoustics of long enclosures. These studies tested the applicability of different prediction methods such as ray tracing (Yang, and Sheild, 2001) and ISM (Li & Lu, 2004; Li & Lu, 2005). The applicability of different prediction methods including ISM and ray tracing methods has been generally validated for the acoustic analysis of long enclosures particularly with rectangular floor-plate shapes. Interestingly, the applicability of hybrid prediction programs that combines the best features of ISM and ray tracing method has not been verified for the acoustic analysis of long enclosures. Additionally, there are very few studies that document the behavior of sound in more complex long enclosures, such as interconnected long enclosures with complex floor-plate shapes (e.g., long enclosures with branches). This study tested the effectiveness of a modeling program that uses hybrid prediction method (CATT-Acoustics V8) in acoustic analysis of both simple and complex long enclosures.

APPENDIX J: JUST NOTICEABLE DIFFERENCE (JND)

Various studies have assessed the reliability of the predicted results via acoustic modeling programs by comparing them with field measured results. The lower the difference between predicted and field measure results, the better the accuracy/precision of the predicted result is. This difference is desired to be as low as possible so that the human auditory system will not perceive the difference. Various studies have been conducted to assess the human auditory system`s ability to perceive the difference between different levels of room-acoustics parameters. The unit of difference is defined as “subjective limen” or “just noticeable difference (jnd)”. If the difference between two levels is less than one subjective limen then the two levels are not perceptibly different. When comparing the measured and predicted results, the most desirable condition is that this difference is less than 1 subjective limen. According to draft international ISO/DIS 3382-1 standard, subjective limen for reverberation time is 5% as shown in Table A.J1 (Bork, 2000).

Table A.J1 Just noticeable difference thresholds for different room acoustic parameters (from ISO 3382).

Parameter	Definition **FDIS 3382-1 [6] (and CEI /IEC 60286-16 [7] for STI)**	Subj. limen
T_{30} (s)	Reverberation time, derived from –5 to – 35 dB of the decay curve	5 %
EDT (s)	Early decay time, derived from 0 to – 10 dB of the decay curve	5 %
D_{50} (%)	Deutlichkeit (definition), early (0 - 50 ms) to total energy ratio	5 %
C_{80} (dB)	Clarity, early (0 – 80 ms) to late (80- ∞) energy ratio	1 dB
Ts [ms]	Centre time, time of first moment of impulse response or gravity time	10 ms
G (dB)	Sound level related to omni-directional free field radiation at 10 m distance	1 dB
LF (%)	Early lateral (5 – 80 ms) energy ratio, $\cos^2$(lateral angle)	5 %
STI (RASTI)	Speech Transmission Index	0.05

However this allowable difference is very small therefore many studies could not obtain results at this precision (Martin, Arana 2005; Shiokawa, & Rindel, 2007). Similarly, program developers also concluded that it is highly difficult or even impossible to obtain results that are within 1 limen range of the measured results (Odeon Tutorial).

The allowable error for reverberation time found by recent studies varied between 4.5% and 10% (Karjalainen, 2001; Niaounakis, 2002). Even higher results were found by a more recent study by Meng, Zhao and He (2006). Measured reverberation JND for different subjects (e.g., audio technicians, common students and audio engineering students) ranged between 21% and 39% (Table A.J2). However, this study used music motifs to approximate the experience of the audiences in the concert halls. The applicability of the results to hospitals is not clear.

Table A.J2 Just noticeable difference thresholds for different room acoustic parameters (from Meng et al., 2006).

Subjects	Instruments	JND at Different Standard Stimulus				Average
		1.0s	2.0s	3.0s	4.0s	
Audio Technicians	Music A	34.5%	22.5%	23.3%	26.3%	26.7%
Common Students	Music B	33.0%	25.8%	25.2%	27.8%	28.0%
	Music A	39.0%	22.5%	25.2%	21.2%	27.0%
Audio Engineering Students	Music A	32.0%	25.3%	26.2%	26.1%	27.4%
	Music C	27.0%	28.5%	26.8%	25.1%	26.9%
	Music B	31.5%	27.8%	26.3%	24.3%	27.5%

Overall, there is not a consensus for the reverberation JND. However, the majority of the validation studies used jnd values suggested by ISO 3382-1 when assessing the difference between measured and predicted results.

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VITA

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